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THE DISPERSION OF METALS IN THE INFRA-RED SPECTRUM

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INTRODUCTION

This paper presents the results of an experimental study¹ of the optical constants of a number of metals, particularly in the region of the infra-red spectrum.

Considerable interest has been manifested in the optical properties of metals during the last two or three decades, as is evidenced by the large amount of work in this field. With the exception of the striking experiments of Kundt² and others on thin prismatic metal films, these properties have generally been determined by the less direct but more accurate method of studying the character of polarization of the reflected light when plane-polarized light is incident on a clean and highly polished surface of the metal at a large angle of incidence.

Prominent among the many investigations in this field stands the work of P. Drude³ who made a very careful study of the optical constants of a large number of metals, chiefly for the wave-length of sodium light. R. S. Minor,⁴ following the photographic method due to W. Voigt,⁵ measured the dispersion of several metals for

¹ This work has been materially aided by grants from the Rumford fund of the American Academy of Arts and Sciences.

² *Wiedemann's Annalen*, **34**, 469, 1888.

³ *Ibid.*, **39**, 481, 1890; **42**, 186, 1891; **64**, 159, 1898.

⁴ *Annalen der Physik*, **10**, 581, 1903.

⁵ *Physikalische Zeitschrift*, **2**, 303, 1901.

the greater part the visible spectrum and extended the work into the ultra-violet with interesting results. Quite recently A. Q. Tool¹ has measured the dispersion of several metals for the visible spectrum, as has also A. L. Bernoulli.² The latter's method, however, has been somewhat criticized by Voigt.³

In the region of the infra-red, on the other hand, practically nothing has heretofore been done. It is true that H. Knoblauch⁴ showed some thirty years ago that effects of elliptical polarization could be obtained by reflecting "heat rays" from a metal surface and that he was even able to conclude that the principal angle of incidence is greater in this region than in the visible spectrum; but he made no attempt at a study of the effect for particular wave-lengths, and his lack of agreement in the case of observations in the visible spectrum with now accepted values shows that his metal surfaces must have been far from the "normal" state.

A study of this problem was undertaken as being part of the general field of work in which the writer has been engaged for several years, viz., the extension into the infra-red spectrum of our knowledge of various optical phenomena which depend on polarization effects, e.g., magnetic rotation, optical constants, etc. In the present case measurements have been made as far into the infra-red as $\lambda = 2.25 \mu$ and these, when combined with the results of other observers, give the dispersion of a number of the more common metals from the ultra-violet to this wave-length of the infra-red spectrum.

METHOD

As is well known, two constants are required to characterize a metal optically— n the refractive index, and k the absorption index. When plane-polarized light is allowed to fall on a polished metal surface it is in general reduced to a state of elliptical polarization because of the relative phase change introduced between the two rectangular components vibrating in and perpendicular

¹ *Physical Review*, **31**, 1, 1910.

² *Annalen der Physik*, **29**, 585, 1909; **33**, 209, 1910.

³ *Ibid.*, **29**, 956, 1909.

⁴ *Festschr. d. naturf. Ges. zu Halle*, 1879; *Nova Acta d. kaiserl. Leop. Carol. deutsch. Ak. d. Naturf.*, **50**, 487, 1887.

to the plane of incidence. For a certain angle of incidence $\bar{\phi}$ (principal incidence), this phase change is 90° , and if the plane-polarized incident beam has a certain azimuth $\bar{\psi}$ (principal azimuth), a circularly polarized beam will result. The constants n and k^1 are connected with these angles by the familiar approximation equations

$$k = \tan 2\bar{\psi}; \quad n = \frac{\sin \bar{\phi} \tan \bar{\phi}}{1 + k^2} \quad (1)$$

The usual method of determining these constants has been through the analysis of the reflected elliptical vibration by measuring the phase-change which must be introduced to reduce it again to a state of plane polarization, as may be done with some such instrument as a Babinet compensator. In the present case it was believed that the principle of the compensator would be difficult of application in the infra-red, so a somewhat different scheme was developed as will be described.

In principle the method is extremely simple. A circularly polarized beam of light is to be distinguished from elliptical by the fact that components of the former taken in any azimuth will all be equal. Such components may be taken by measuring the intensity (or rather amplitude) of the beam after passage through any polarizing agent, e.g., a nicol. When, for any particular wave-length, the azimuth of the plane-polarized incident beam as well as its angle of incidence has been adjusted until all such components are found equal, that is, until the reflected beam is circularly polarized, then these angles are the principal azimuth and incidence respectively, and the optical constants are computed from them by the foregoing relations.

The use of a nicol in this connection, however, would entail certain difficulties which may be overcome if it be replaced by a double-image prism. For this prism gives in its two transmitted

¹ The constant n has the same meaning as for transparent substances. The constant k has the following significance: The amplitude of a wave after traveling one wave-length, λ' measured in the metal, is reduced in the ratio $1 : e^{-2\pi k}$, or, more generally, for any distance d in the metal the amplitude is reduced by the factor

$\frac{1}{e^{-\frac{2\pi dk}{\lambda'}}$ For the same wave-length measured in air, this factor would be $\frac{1}{e^{-\frac{2\pi d n k}{\lambda}}}$.

The product nk is sometimes called the extinction coefficient.

beams two rectangular components of the incident vibration, and when these components are equal—regardless of how the prism is rotated about the axis of this beam—then the beam is circularly polarized, granted that it is not entirely unpolarized. The necessity for rotating the double-image prism relative to the beam is readily seen, since it is evident that an elliptical or even plane-polarized vibration would possess equal components for certain azimuths, but only a circular one, equal components for all azimuths.

APPARATUS

The general arrangement of apparatus is shown in the diagram of Fig. 1 and the photograph, Fig. 2, the lettering being arranged to correspond in the two cases. Light from a water-jacketed Nernst glower G_1 , after being rendered parallel by the concave mirror M_1 , was plane polarized by P_1 and then fell on S , the metallic surface to be studied. The angle of incidence on S could be varied at will, since the glower, mirror, and polarizer were mounted on an arm which rotated around the axis xx' . The beam reflected from S would in general be elliptically polarized, but was reduced on passing through the double-image prism P_2 (P_3 being removed) to two rectangular components with a small angle of divergence between them. Because of this angle of divergence there were formed on the slit Sl , on reflection from the concave mirror M_2 , two images of the glower vertically separated from each other by about one centimeter. Consequently on passage through the spectrometer two spectra were formed and these fell on the two strips of a special bolometer which had strips vertically over one another and so connected that when they were illuminated by beams of equal intensity no deflection of the galvanometer resulted.

The principle of operation in brief was so to determine the angle of incidence and azimuth of the plane-polarized beam falling on S that a truly circular vibration should result. The angle of incidence could be changed, as already noted, by turning the polarizing part of the apparatus about the axis xx' , while the azimuth was altered by rotating the polarizer in its mounting. The circularly polarized beam was recognized as such by the equal intensity of the

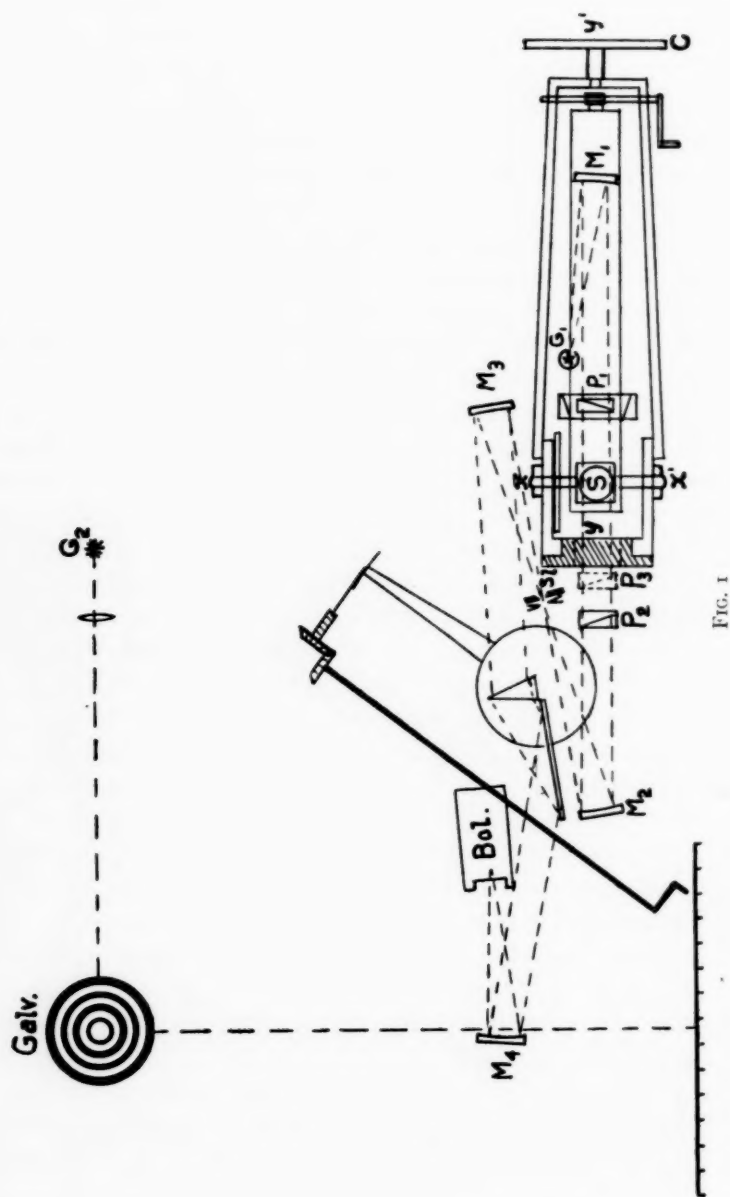
two beams from the analyzer; that is, by the fact that the galvanometer showed no deflection, the spectrometer being set for some chosen wave-length. But, as before stated, to be sure the vibration is circular it must be possible to rotate the analyzer relative to the beam. This would apparently be a very simple thing to do until it is considered that this would result in displacing the two images of the glower, i.e., the foci of the two beams, off the slit. To avoid this and still accomplish the purpose, the entire polarizing part of the apparatus, including the metal surface (but excluding the analyzer), was arranged so that it could be rotated about a horizontal axis yy' . In the photograph it is shown as turned about twenty degrees to the right from its vertical or zero position.

The spectrophotometric part of the apparatus was that already used by the writer in a study of magnetic rotation, and for a detailed description of the spectrometer, bolometer, and galvanometer the reader is referred to this paper.¹ Suffice it to say here that the spectrometer might be used with either of two large glass prisms of angles 25° and 45° and of such dispersive powers that the latter gave a spectrum of some two or three times the breadth of the former; the use of these two prisms will be discussed in connection with sources of error. It may be noted that the use of a prism of glass rather than of rock salt was permissible, since the limit of the spectral range to which it is possible to work is fixed by the absorption of the calcite of the polarizing apparatus, which is about the same as that of glass.

The bolometer strips were each $\frac{1}{2}$ mm \times 8 mm and, as already noted, so arranged that when both were exposed to beams of equal intensity the galvanometer showed no deflection. The galvanometer itself was of the Thomson type with a sensibility of about 5×10^{-10} amperes per mm for a scale one meter distant. The magnetic shield which surrounded it gave a shielding effect of about six thousand fold.

Polarizing agents.—For this purpose double-image prisms were exclusively used. The reason for using one as an analyzer has already been discussed, but it is not evident without explanation why one would also serve as polarizer, since here only a single beam

¹ *Phil. Mag.* (6), **18**, 74-102, July 1909.



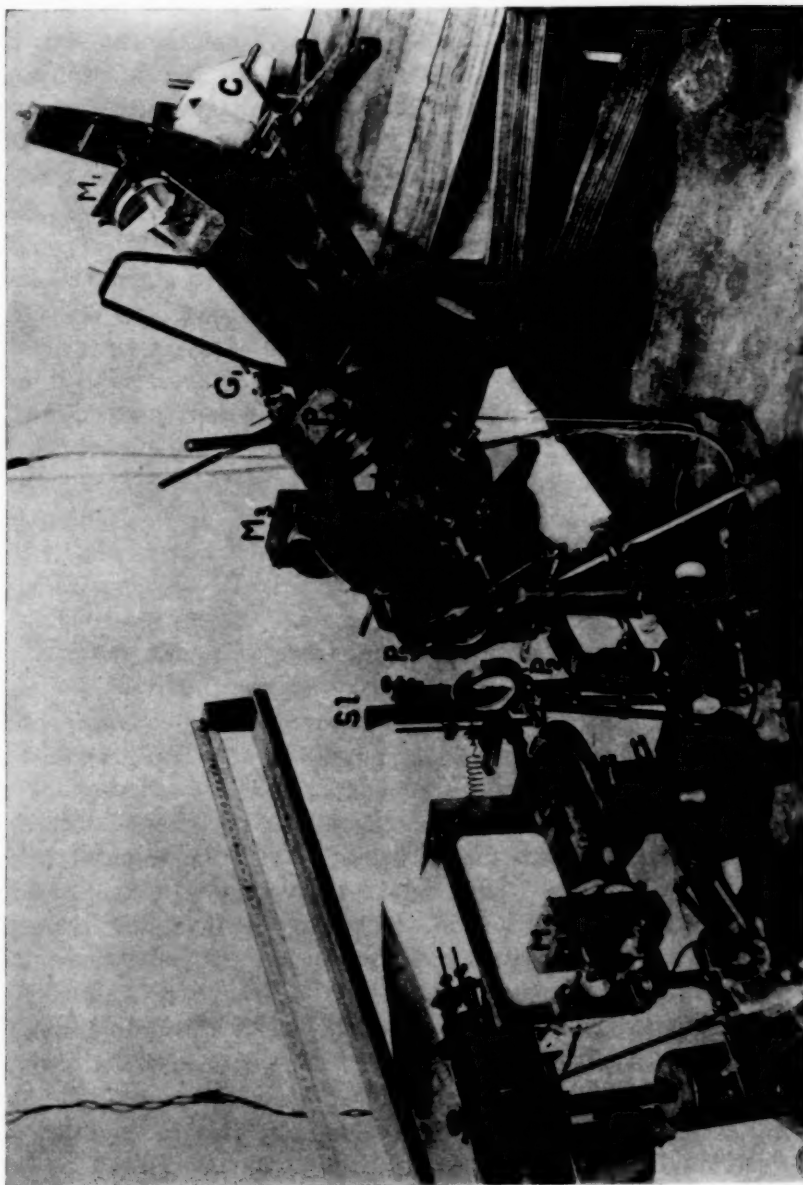


FIG. 2

of plane-polarized light was wanted. But the single beam was readily secured from the double-image polarizer, as one of the two beams was deviated so as to miss the slit entirely and hence be of no effect. The practical reasons for using a double-image prism instead of a nicol in this connection were the smaller thickness of glass and calcite necessary, and the ease of securing a larger aperture.

The polarizer P_1 was of the Rochon type, of calcite achromatized with glass, giving a separation of the two beams of about 1° . It was of about 40 mm aperture. The analyzer P_2 was a large Wollaston prism of 48 mm aperture of such angle as to give a separation of $2^\circ 25'$ between the two rays. A third prism P_3 was also used in the latter part of the work in a way which will be mentioned in a discussion of errors. The three prisms were splendid specimens of optical work, having been specially made by Messrs. Steeg and Reuter.

Other instrumental details may briefly be mentioned. Mirrors M_3 and M_4 were of 10 cm aperture and 30 cm focal length each; M_1 and M_2 of 8 cm aperture and of 23 cm and 30 cm focal length respectively. It was found necessary to surround the glower G_1 with a jacket to secure constancy of radiation, and the jacket itself had to be water-cooled to keep down its own radiation. The polarizer P_1 was mounted in a large conical brass bearing carrying a divided circle with vernier reading to $2'$. This was accordingly the limit of accuracy for reading azimuths. The glower, mirror, and polarizer were carried on a large arm which could be rotated about the axis xx' by rack and pinion and could also be rigidly locked at any angle. The main circle about this axis was divided to half-degrees and carried a vernier reading to $1'$, whence the angle of incidence was determinate to $0.5'$. The metallic surface S was mounted on an adjustable table pivoted about this same axis. A rough circle C at the end y' sufficed to give the angle about the axis yy' .

PROCESS OF MAKING OBSERVATIONS

That one may understand the conditions which make for accuracy as well as for error in the results, the process of measuring optical constants must be described in some detail. Let it be

supposed that the apparatus, including the spectrometer, had been carefully aligned and adjusted and that the polarizer was turned so that its principal plane made an angle of 45° with each of the two planes of the analyzer. Then the vibration transmitted by the polarizer should have had the same component in each of the analyzer sections, hence if the galvanometer did not stand at zero (that is, show equal intensity of radiation on each bolometer strip) it would be because of unequal absorption of the two beams on their subsequent passage through the spectrometer. This was corrected for by screening off a small fraction of one or the other image as it fell on the slit, by a little device¹ which moved directly across and in front of the slit on a screw. This was turned until the deflection was zero and then one might be assured that, when in the analysis of any sort of vibration, the deflection reduced to zero, the two components of the vibration were equal. This process may be referred to as that of "setting the bolometer zero."

Having made this preliminary adjustment with the spectrometer set for any chosen wave-length, the metallic surface was put in place and an angle of incidence chosen which was thought to be near the principal incidence. The azimuth of the polarizer was then varied till the galvanometer regained its zero position, indicating the equality of the two reflected components.

In general, however, this would not mean a truly circular vibration but rather an elliptical one, so oriented that it gave equal components.² To detect this the polarizing arrangement including the metallic surface was rotated 45° about the axis of the beam yy' first to the right and then to the left, and an elliptical vibration would be shown by the corresponding galvanometer deflection, which would be first to the one side and then to the other, respectively. Having noted these deflections, a second setting of the angle of incidence and its corresponding azimuth was made, and usually a third setting could be chosen so well as to produce an almost exactly circular vibration. In that case the azimuth and

¹ See *Phil. Mag.* (6), **18**, 81, July 1909.

² For a further discussion of this point see a paper by Mr. Littleton and the writer in *Physical Review*, November 1910, on the application of this method in a visual polarimeter.

incidence would be the principal azimuth and incidence respectively. A second determination of the azimuth in another quadrant of the polarizer should yield the same result. If it did not, it meant that the zero point for measurements of the rotation about the axis yy' was at fault. This was located by a stop which had to be occasionally adjusted. In general a careful determination of the principal angles for any one wave-length could be made in fifteen or twenty minutes.

ERRORS

The following sources of error have been studied:

Use of approximation equations.—When a method of measuring optical constants—e.g., Babinet compensator—affords a direct determination of the phase difference between the two components of vibration for any angle of incidence, rigorous equations for computing the constants are available. On the other hand when, as in many cases including the present, only the principal angles are directly measured, the rigorous equations are not directly applicable and the approximation relations (1) are those in general use. These may result in an error of several per cent in the constants, but fortunately this can be almost entirely eliminated by the use of a sort of correction factor,¹ a simple function of the square of the cotangent of the principal incidence, which is applied as follows:

If we call the values of the constants computed by (1)

$$k' = \tan 2\bar{\psi}, \text{ and } n' = \frac{\sin \bar{\phi} \tan \bar{\phi}}{1 + k'^2},$$

then values n and k which are much more nearly correct are given by

$$k = k'(1 - \cot^2 \bar{\phi}), \text{ and } n = n'(1 + \frac{1}{2} \cot^2 \bar{\phi}) \quad (2)$$

These equations (2) have been tested by applying them in connection with (1) to a number of the principal angles listed by Drude and Minor. The results afforded were in general in good agreement with their tabulated values of the constants.

Condition of surfaces.—The various precautions to avoid films, which were taken in the preparation and cleaning of the surfaces,

¹ P. Drude, *Annalen der Physik*, **36**, 546, 1889.

will be considered in a discussion of the results, but the degree of success in obtaining perfect surfaces may be mentioned here. When the dispersion curves obtained for the various metals were extrapolated from $\lambda = 0.65 \mu$ back to the wave-length of sodium light the values they afforded of the constants were, with one or two exceptions, in sufficiently good agreement with the accepted values for these metals to warrant considering the surfaces in the normal condition. In the case of steel, however, all the surfaces gave values of the principal incidence from $20'$ to 1° too small. This pointed very clearly to surface imperfections or films, and while they could not be entirely eliminated they were readily allowed for by adding a small correction to the principal incidence as measured. The results for the several steel surfaces were in much better agreement for the longer wave-lengths than for the shorter, hence this correction was reduced from about $20'$ at $\lambda = 0.65 \mu$ to only $8'$ at $\lambda = 2 \mu$. This is much smaller than the correction made by Minor to his measurements on cobalt.

Low dispersion.—Since an error might be expected to arise from the low dispersion of the 25° prism, a large number of the measurements were repeated using the 45° prism of heavy glass giving a spectrum of perhaps three times the dispersion. No appreciable discrepancy between the two sets of results could be detected. The wave-length scale for both prisms was determined by double dispersion with the aid of a second prism of rock salt. It was also checked by locating the absorption bands in sunlight.

Azimuth determinations.—The consistency of successive incidence and azimuth settings was remarkable. Under favorable conditions indeed it was apparently limited only by the accuracy with which the circles could be read. That is, a very small *change* (much smaller, for certain reasons than could even be detected on the circles) could be measured, and on this account some experiments will shortly be carried out with this apparatus with the view of detecting any possible change in the constants which may be brought about by giving the metallic surface an electric charge, i.e., by adding to its number of electrons. As it is believed that its sensibility in the detection of such an effect can be made from

ten to one hundred times greater than that possible with visual methods, the experiment seems worth trying.

In the matter of absolute determinations of the constants, however, the possible accuracy is very much less than would be concluded from the above discussion, for successive measurements with intervening changes in the adjustment of the apparatus do not show any such consistency. Rather curiously perhaps, the error seems to be confined almost entirely to principal azimuth determinations and for only the longer wave-lengths. Some specific results will illustrate this point: thus for nickel at $\lambda = 1.75 \mu$ three principal incidence measurements made under as many different instrumental arrangements and adjustments gave $83^\circ 20'$, $83^\circ 26'$, and $83^\circ 25'$, while four corresponding principal azimuth determinations were $32^\circ 33'$, $34^\circ 3'$, $33^\circ 27'$, and $32^\circ 51'$. On the other hand, for $\lambda = 0.65 \mu$ the principal incidences as found were $77^\circ 30'$, $77^\circ 48'$, and $77^\circ 47'$, while the azimuths came $32^\circ 28'$, $32^\circ 28'$, $32^\circ 46'$ and $32^\circ 34'$.

These results, which are very fair samples of those obtained for any metal, show at once that the error is confined to the azimuth determinations and is of a serious nature only for the longer wave-lengths. The limits of error, however, are not quite as great as these figures would cause one to conclude, for, in the case of the latter two of the four azimuths listed for each wave-length, an important modification was adopted in the method of setting the bolometer zero. This involved the introduction of a third double-image prism P_3 with its planes set at 45° to those of the analyzer P_2 . This was mounted so that it could be temporarily turned into position in front of P_2 and removed as soon as the bolometer zero had been set. Before the introduction of this third prism the azimuth determinations had been found to depend in some measure on a number of apparently extraneous conditions such as the shape and size of the aperture limiting the beam, the condition of the Nernst glower, etc. But by its use these effects were almost entirely removed, hence the last two azimuth measurements have greater weight than the others. But even at best the accurate determination of principal azimuths for wave-lengths about 1.75μ or longer is extremely difficult, since for these longer waves conditions are

complicated by a dispersive effect arising from the polarizing agents. Until an extensive study can be undertaken of these various effects it must suffice to accept the most probable values and to estimate the limits of error involved.

One other source of error in the azimuth measurements has been considered. Because of the length of glower and image necessary to get sufficient energy the radiation was incident on the metal surface over a range of angle of about 1° , but careful tests of this source of error indicate that it is negligible in comparison with that just mentioned.

Visual measurements with a Babinet compensator, using sodium light, were made on the steel, nickel, cobalt, and silicon surfaces. The principal azimuths agreed in most cases very well with the points taken from the extrapolated infra-red curve, but the principal incidences came a few minutes low. This might perhaps be interpreted as meaning that the method yields slightly too high results for the principal incidence, although the measurements on silicon would not bear out this conclusion; but in any event, since the tendency of any surface impurities is to reduce the principal incidence, this error is in a measure self-eliminating.

The effect of these sources of error on the final results has been carefully considered and an estimate of the probable limits of error is included with each set of results. In the case of steel, nickel, and cobalt it will be observed that the limits of error are not much larger, save in the case of the longer waves, than might reasonably be expected for visual observations. For copper and silver, however, the limits are large, for the azimuths are so nearly 45° that the effects of small errors are greatly magnified.

RESULTS

Six different metals were tested in all, viz., steel, nickel, cobalt, silver, copper, and silicon. This includes the four used by Minor and in addition nickel and silicon. Although the latter has small claim to being considered a metal in this connection, the results are not without interest.

Surfaces.—As might be anticipated, one of the greatest difficulties encountered was the securing of suitably polished sur-

faces. It may be observed that the present requirements in the way of a plane and polished surface were considerably more rigorous and difficult of fulfilment than if the work had been confined to the visible spectrum. For visual observations can be made on a surface of only a few square millimeters in area and of only the roughest approximation to planeness, while in the present infra-red work the accuracy of the measurements was largely dependent on the area of surface available, and this surface had to be plane to a few wave-lengths of light.

After discouraging experiences with some of the best optical workers, some very fair surfaces were prepared in this laboratory with a deal of difficulty; later, two or three very excellent surfaces were polished by Zeiss. A detailed description of the specimens tested will be given in connection with the specific results, but some general considerations applying to all may be mentioned here.

Even after a comparatively perfect surface of any particular metal had been obtained, the values of the constants it afforded still depended to some extent on the manner in which it had been cleaned. It is usually considered allowable to clean such a surface with absorbent cotton and alcohol, but it was found that even with the purest alcohol obtainable and with the least possible rubbing with cotton, indications of surface films were still sometimes obtained, and in the case of steel the best results were obtained just after polishing with rouge on dry chamois skin and without further cleaning.

Purity.—From what has been said it will be granted that the prime factor in such work as this is the condition of the surface, and this overshadows in importance even the question of the purity of the metal itself. Every effort was made, however, to secure specimens as pure as possible. The copper and silicon were each of tested purity 99.8 per cent or better. The silver, which was deposited chemically, was probably not as pure as this, while the steel specimens were of high-grade tool steels, but of unknown purity. The cobalt and nickel were from sheet material from Kahlbaum. While they were the best obtainable in this form, chemical tests indicated the presence of perhaps 2 per cent of cobalt in the nickel, and probably there was at least as much nickel

in the cobalt. It is very likely, however, that they were of the same order of purity as the specimens of these metals tested by Drude, Minor, and others.

Determinations to the number of many hundred have been made of the principal angles of the various metals, and for upward of twenty wave-lengths, but after it was found that the dispersion-curves were quite regular in form, it was thought best to concentrate the efforts on measurements for only a few wave-lengths, with the view of determining the constants for these points as accurately as possible. Nine points in the spectrum, ranging from $\lambda=0.65 \mu$ to 2.25μ , were accordingly chosen and repeated determinations made for these wave-lengths. Later this number was reduced to only five, viz., $\lambda=0.65 \mu$; 0.87μ ; 1.25μ ; 1.75μ ; 2.25μ . The final and presumably most accurate measurements were made for these wave-lengths only. Also since it was found that the use of the 25° prism, in spite of its low dispersion, led to no appreciable error, it was used almost exclusively, thereby furnishing more energy in the spectrum and hence allowing more accurate measurements.

The results of the present work listed in the tables have been arrived at as follows: All the worthy determinations of the principal angles for any given metal were plotted with wave-length. The best average curves were then drawn and the angles given in the first two columns were taken from these curves; the constants were computed from these angles in the way already described.

To give a general survey of the whole spectral region which has been studied to date in the case of metals, some of the results of Minor and others have been included in the tables and curves. Following the practice of Drude, the results are expressed in general to only two decimals, as the discrepancies between different observers extend into even the first decimal place. For purposes of comparison with the theoretical reflecting powers as computed from these constants, the measurements of Hagen and Rubens¹ on reflecting powers of metals are also listed.

Steel.—Five surfaces of tool steel were experimented upon. Four of these ranging in size from $2 \text{ cm} \times 2 \text{ cm}$ to $3 \text{ cm} \times 7 \text{ cm}$ were

¹ *Annalen der Physik*, **8**, 1, 1902; see also *Phil. Mag.* (6), **7**, 162, 1904.

polished in this laboratory. The method used on the larger pieces was to polish dry on graded emery paper, finishing with wet rouge on a pitch tool in a polishing machine. Others were ground with graded carborundum on a wet lead plate and finished with rouge on pitch. A surface by Zeiss 2 cm \times 4 cm was also available through the kindness of Professor Minor. This was the one used by him in his measurements on steel, but unfortunately it was not in as perfect condition as originally. The various surfaces gave results in fairly good agreement, especially for the longer wave-lengths, but the principal incidences were all slightly too

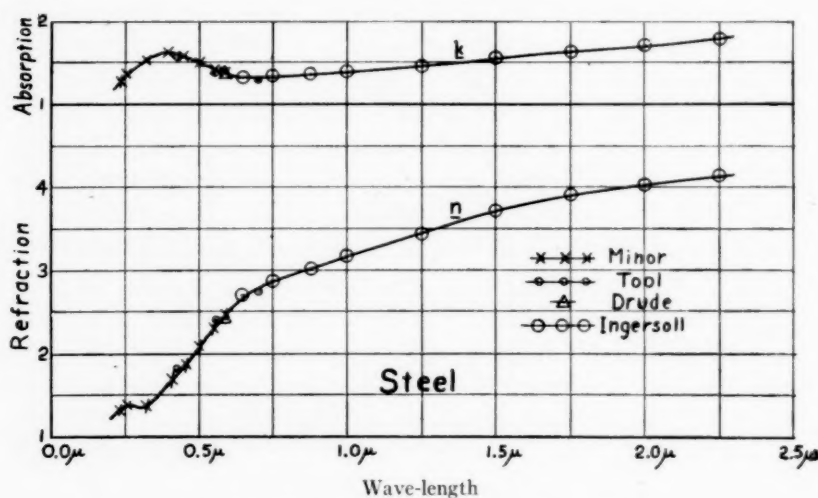


FIG. 3.—Curves showing the dispersion of steel

low for the shorter wave-lengths (in comparison with the values of Drude and others), necessitating a small correction as explained in a consideration of the sources of error.

The results are contained in Table I and are shown graphically in the curves of Fig. 3. The best estimate it is possible to make of the limits of error places them at perhaps ± 0.07 at $\lambda = 0.65 \mu$, increasing gradually to ± 0.20 at 2.25μ . This is for the refractive index n ; the corresponding limits for k are ± 0.03 and ± 0.10 . In addition to Hagen and Rubens' reflecting powers a measurement

by Trowbridge on the reflecting power of iron for 2.00μ is included. It may be observed that in this as well as in succeeding tables it has been frequently necessary to interpolate the Hagen and Rubens determinations to secure data for the particular wave-lengths here used.

TABLE I
STEEL

λ	ϕ	ψ	n	k	nk	Authority	R (Com- puted)	R (Hagen and Rubens)
0.226 μ	66° 51'	28° 17'	1.30	1.26	1.64	Minor	34.8%	....
.257	68 35	28 45	1.38	1.35	1.86	Minor	39.6	33.0%
.325	69 57	30 9	1.37	1.53	2.09	Minor	44.8	40.3
.400	73 39	30 16	1.68	1.62	2.72	Minor	53.9	49.6
.420	74 9	29 48	1.79	1.57	2.82	Tool	54.5	51.9
.450	74 48	29 36	1.88	1.57	2.93	Minor	55.4	54.4
.500	75 47	29 2	2.09	1.50	3.14	Minor	56.9	54.8
.550	76 35	28 18	2.31	1.43	3.30	Minor	57.7	54.9
.560	76 39	27 24	2.40	1.34	3.21	Tool	56.1	55.0
.589	77 9	27 45	2.48	1.38	3.43	Minor	58.4	55.3
.589	77 3	27 49	2.41	1.38	3.40	Drude	58.5	55.3
.650	77 48	27 9	2.70	1.33	3.59	Ingersoll	59.2	56.8
.700	77 36	26 36	2.73	1.27	3.47	Tool	58.0	57.6
.750	78 28	27 8	2.86	1.33	3.80	Ingersoll	61.2	58.0
.870	79 9	27 16	3.02	1.35	4.08	Ingersoll	63.2	59.4
1.00	79 48	27 33	3.19	1.39	4.43	Ingersoll	65.5	63.1
1.25	80 55	28 15	3.45	1.47	5.08	Ingersoll	69.7	68.8
1.50	81 48	28 51	3.71	1.55	5.75	Ingersoll	73.1	70.8
1.75	82 26	29 28	3.88	1.63	6.32	Ingersoll	75.6	....
2.00	82 55	30 1	4.02	1.71	6.88	Ingersoll	77.7	{ 76.7
2.25	83 22	30 36	4.14	1.79	7.41	Ingersoll	79.7	{ 78.7*
							

* See paper by A. Trowbridge, *Wiedemann's Annalen*, 65, 595, 1898.

Cobalt.—The results are shown in Table II and Fig. 4. They were obtained with a surface 5 cm in diameter polished by Zeiss. The quality of the surface was very good indeed, as it contained only one or two small imperfections and showed a brilliant mirror-like polish without scratches. The estimated limits of error are, for n , from ± 0.03 at $\lambda = 0.650 \mu$ to ± 0.26 at 2.25μ . The corresponding limits for k are ± 0.02 and ± 0.06 .

TABLE II
COBALT

λ	$\bar{\phi}$	$\bar{\psi}$	n	k	nk	Authority	R (Computed)
0.231 μ	64° 31'	29° 39'	1.10	1.30	1.43	Minor	31.8 %
.275	70 22	29 59	1.41	1.52	2.14	Minor	45.7
.347	72 18	30 20	1.54	1.61	2.47	Minor	51.1
.395	74 15	31 20	1.63	1.79	2.91	Minor	57.7
.440	75 18	31 45	1.70	1.87	3.19	Tool	61.1
.450	76 8	31 52	1.79	1.91	3.42	Minor	63.3
.500	77 5	31 53	1.93	1.93	3.72	Minor	65.5
.550	77 40	31 43	2.05	1.91	3.90	Minor	66.6
.560	77 30	31 12	2.09	1.82	3.81	Tool	65.3
.589	78 5	31 40	2.12	1.90	4.04	Drude	67.5
.650	79 0	31 25	2.35	1.87	4.40	Ingersoll	69.2
.680	79 12	30 45	2.50	1.77	4.44	Tool	68.7
.750	80 2	30 48	2.71	1.79	4.85	Ingersoll	71.0
.870	81 4	30 0	3.18	1.60	5.37	Ingersoll	72.5
1.00	81 45	29 6	3.63	1.58	5.73	Ingersoll	73.3
1.25	82 44	27 30	4.50	1.40	6.30	Ingersoll	74.3
1.50	83 21	26 18	5.22	1.29	6.73	Ingersoll	75.1
1.75	83 33	25 39	5.53	1.23	6.81	Ingersoll	75.1
2.00	83 41	25 39	5.65	1.23	6.95	Ingersoll	75.7
2.25	83 48	26 5	5.65	1.27	7.18	Ingersoll	76.5

Nickel.—The best nickel surface used was one polished by Zeiss, quite similar to the cobalt surface. The limits of error run from ± 0.04 at $\lambda = 0.650 \mu$ to ± 0.26 at 2.25μ , for n ; and from ± 0.06 to ± 0.15 for k .

TABLE III
NICKEL

λ	$\bar{\phi}$	$\bar{\psi}$	n	k	nk	Authority	R (Computed)	R (Hagen and Rubens)
0.420 μ	72° 20'	31° 42'	1.41	1.79	2.53	Tool	53.7 %	56.6 %
.436	75 23	31 3	1.74	1.89	3.28	Bernoulli	61.9	58.1
.492	75 40	31 20	1.74	1.93	3.37	Bernoulli	63.1	60.7
.500	74 20	32 15	1.54	1.93	2.97	Tool	59.7	60.8
.578	76 0	31 40	1.75	1.99	3.48	Bernoulli	64.4	63.9
.589	76 1	31 41	1.79	1.86	3.33	Drude	62.0	64.4
.615	76 48	31 49	1.85	2.01	3.73	Bernoulli	66.3	65.1
.650	77 35	32 35	1.91	2.06	3.93	Ingersoll	67.8	67.2
.700	77 50	32 3	2.02	1.96	3.98	Tool	67.6	68.8
.750	78 45	32 6	2.19	1.99	4.36	Ingersoll	69.6	69.1
.870	79 44	31 51	2.45	1.96	4.80	Ingersoll	71.7	71.0
1.00	80 33	32 2	2.63	2.00	5.26	Ingersoll	74.1	73.0
1.25	81 47	32 31	2.92	2.11	6.15	Ingersoll	78.0	77.3
1.50	82 42	32 53	3.21	2.18	7.00	Ingersoll	80.6	79.9
1.75	83 22	33 10	3.45	2.25	7.76	Ingersoll	82.7	...
2.00	83 55	33 24	3.70	2.31	8.54	Ingersoll	84.4	83.5
2.25	84 21	33 30	3.95	2.33	9.20	Ingersoll	85.3	...

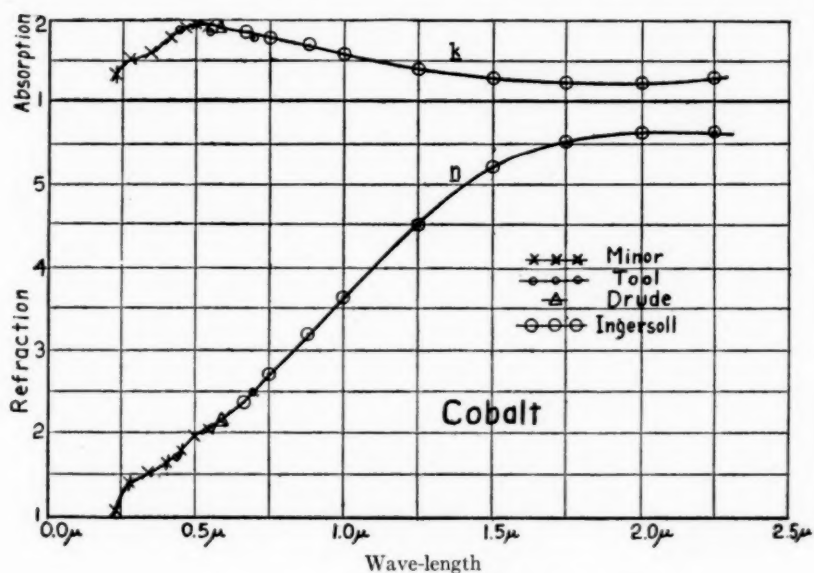


FIG. 4.—Curves showing the dispersion of cobalt

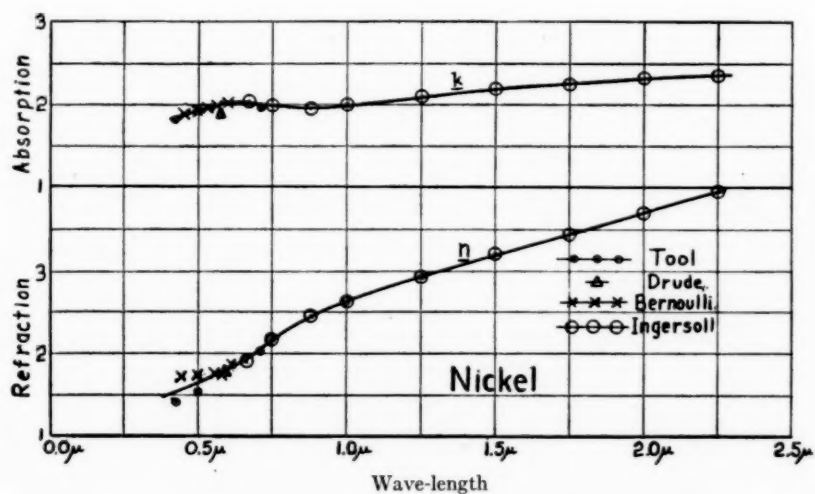


FIG. 5.—Curves showing the dispersion of nickel

Silver.—Because of the great effect of a small error in azimuth (this being so nearly 45°), this was perhaps the hardest metal to test. A considerable area of plane surface was required, and, everything considered, it was thought best to use for this purpose a chemically silvered glass plate. For while it is known that silver in this form will not yield results absolutely identical with those obtained with surfaces on the massive metal, such errors are small compared with the necessary experimental errors in this case.

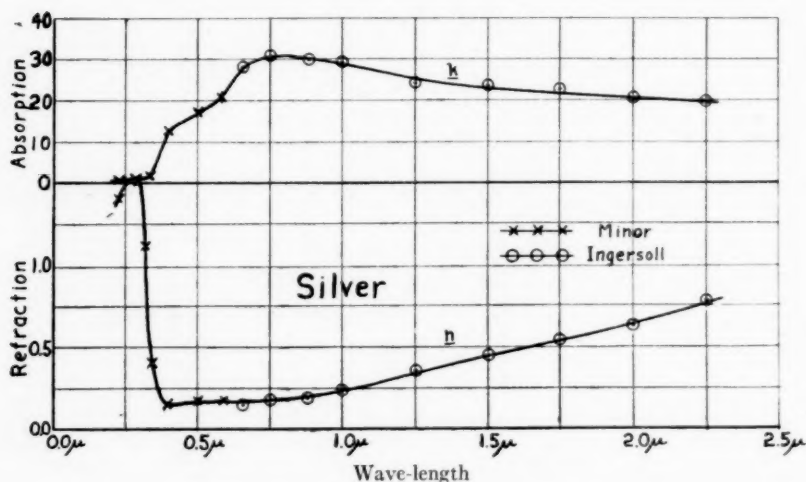


FIG. 6.—Curves showing the dispersion of silver

Accordingly a piece of plate glass, $6\text{ cm} \times 10\text{ cm}$, of tested planeness, was silvered by the Brashear process and polished with rouge on chamois. The measurements were made immediately after polishing.

For purposes of comparison the values of nk obtained by Hagen and Rubens¹ are included, the figures for these particular wave-lengths having been necessarily interpolated in many cases. The agreement is fairly good and probably well within the limits of error which are very large in this case, especially for the longer wave-lengths, because, as noted above, of the great effect of small

¹ *Annalen der Physik* (4), 8, 432, 1902.

errors in the azimuth determinations. They run from ± 0.03 at $\lambda = 0.650 \mu$ to ± 0.40 at 2.25μ for n ; and for k from ± 4.0 to probably ± 10.0 (i.e., 50 per cent).

TABLE IV
SILVER

λ	ϕ	ψ	n	k	nk	Authority	R (Computed)	Hagen and Rubens' Observed Values	
								nk	R
0.226 μ	62° 41'	22° 16'	1.41	0.75	1.11	Minor	18.4%	....	....
.293	63 14	18 56	1.57	0.62	0.97	Minor	16.7	0.95	15.0
.316	52 28	15 38	1.13	0.38	0.43	Minor	4.2	0.45	4.2
.332	52 1	37 2	0.41	1.61	0.65	Minor	32.5	0.55	35.5
.395	66 36	43 6	0.155	12.32	1.91	Minor	87.1	1.94	83.4
.500	72 31	43 29	0.169	17.14	2.94	Minor	93.2	3.21	91.3
.589	75 35	43 47	0.177	20.55	3.64	Minor	95.0	4.12	92.7
.650	77 35	44 2	0.154	28.2	4.34	Ingersoll	96.9	4.77	95.7
.750	79 26	44 6	0.168	30.7	5.16	Ingersoll	97.4	5.85	96.6
.870	80 54	44 4	0.203	29.9	6.07	Ingersoll	97.8	6.76	97.2
1.00	82 0	44 2	0.24	29.0	6.96	Ingersoll	98.1	8.0	97.5
1.25	83 40	43 50	0.37	24.1	8.88	Ingersoll	98.2	10.7	97.7
1.50	84 42	43 48	0.45	23.7	10.7	Ingersoll	98.4	12.4	97.9
1.75	85 24	43 44	0.55	22.4	12.3	Ingersoll	98.5	....	....
2.00	85 55	43 36	0.68	20.3	13.7	Ingersoll	98.5	....	97.8
2.25	86 18	43 34	0.77	19.9	15.4	Ingersoll	98.6	....	....

Copper.—The copper surface was polished by Zeiss on a 5 cm plate of electrolytic copper of great purity. While probably the best which could be produced, at least on this specimen, the polish was far from good. To improve this and to remove the small amount of oxidation which had formed since it had been finished, it became necessary to "buff" the surface to produce a polish which would yield optical constants in even fair agreement with accepted values. This fact, together with the large azimuth afforded by copper and its consequent attendant errors, renders the results obtained with this metal the least satisfactory of any. The limits of error are from 30 per cent to 50 per cent of the results themselves, i.e., for n from ± 0.15 to ± 0.35 , and for k from ± 2.5 to ± 5.0 . Both for silver and copper the figures for wave-length greater than say 1.5μ can be considered only as indicative of the general trend of the curves.

TABLE V
COPPER

λ	$\bar{\phi}$	$\bar{\psi}$	n	k	nk	Authority	R (Com- puted)	R (Hagen and Rubens) †
0.231 μ	65° 57'	26° 14'	1.39	1.05	1.45	Minor	29.0%	....
.347	65 6	28 16	1.19	1.23	1.47	Minor	31.5	26.4%
.450	69 41	32 39	1.13	1.90	2.15	Minor	50.5	37.0
.460	70 36	32 45	1.18	1.93	2.28	Tool	52.6	38.3
.500	70 44	33 46	1.10	2.13	2.34	Minor	55.5	43.7
.589	71 34	39 5	0.62	4.26	2.63	Minor	74.1	64.0
.650	74 16	41 30	0.44	7.4	3.26	Ingersoll	86.2	80.0
.660	76 12	40 24	0.65	5.77	3.78	Tool	84.6	80.7
.870	78 40	42 30	0.35	11.0	3.85	Ingersoll	91.5	89.0
1.25	82 14	42 50	0.56	13.0	7.28	Ingersoll	95.8	93.6
1.75	84 4	42 30	0.83	11.4	9.46	Ingersoll	96.4	....
2.25	85 13	42 30	1.03	11.4	11.7	Ingersoll	97.1	96.0

Silicon.—The silicon was in the form of a plate of perhaps 3 sq. cm area, and was polished by Mr. J. T. Littleton, Jr., of this laboratory from a crystal of 99.75 per cent purity furnished by the Carborundum Company of Niagara Falls.

TABLE VI
SILICON

λ	$\bar{\phi}$	$\bar{\psi}$	n	k	nk	R (Computed)
0.589 μ	76° 36'	2° 42'	4.18	0.090	0.377	37.7%
0.870	75 11	2 29	3.77	0.081	0.305	33.9
1.25	74 51	2 28	3.67	0.080	0.293	32.8
1.75	74 31	2 29	3.59	0.080	0.287	31.7
2.25	74 16	2 25	3.53	0.078	0.275	31.3

Discussion of the results.—The most obvious thing to be noted from the tables and curves is the fact that for the first five metals the refractive indices all show an increase with increasing wavelength. In the case of steel, nickel, and cobalt this rise of the dispersion-curve is merely a continuation of the tendency shown by visual observations, but in the case of copper and silver it could not be predicted. That this increase is not as rapid, however, as would be judged from such visual observations, is shown by the curves for steel and particularly for cobalt, where the

refractive index has apparently reached a maximum at wave-length 2.00μ .

The absorption index curves, on the other hand, show no such general tendency. A gradual rise on the side of the infra-red in the case of steel and nickel and a corresponding lowering for the other three metals may be noted, but in general the change is less after the visible spectrum has been passed and the infra-red reached. This means that the product nk , the extinction coefficient, increases in general with the wave-length.

In silicon, on the other hand, the refractive index shows a

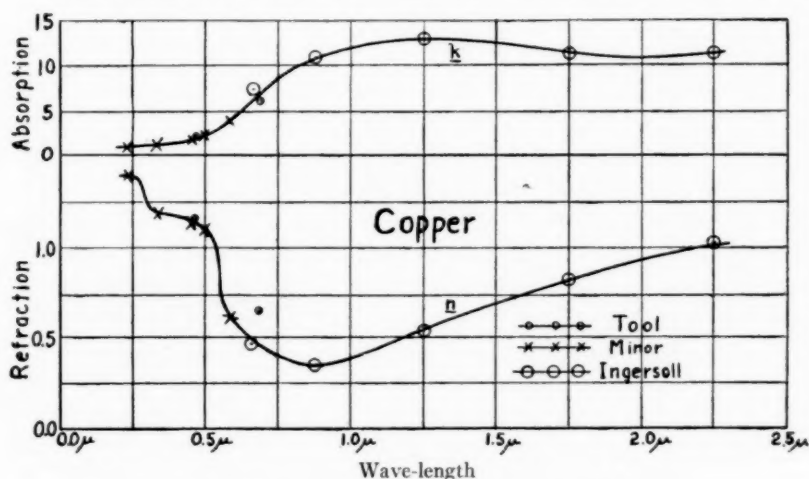


FIG. 7.—Curves showing the dispersion of copper

small decrease as the wave-length increases, in the same sense and of much the same order of magnitude as exhibited by dielectrics. The reflecting powers, too, show a decrease on the side of the infra-red, just as in the case of dielectrics, and these facts should go far to remove what small claim silicon may have to be considered a metal, optically speaking.¹

Comparison with theory.—In attempting to compare the results with theory the same difficulty is encountered that is generally met with in any attempt at reconciling in a quantitative way the

¹In other words, silicon has a much larger proportion of non-conducting, or "bound," electrons than most other metallic substances.

predictions of the electromagnetic theory with experimental facts. To bring about an agreement the equations are complicated by terms which take into account, in the case of metals, the presence of conducting and bound electrons, and involve coefficients which it is well-nigh impossible to determine in many cases.

But while the agreement of the metals with the simple Maxwell theory may be very poor for the region of the visible spectrum, Hagen and Rubens¹ find that for wave-lengths longer than about 8.85μ the agreement of optical and electrical properties is very nearly such as demanded by this theory. It becomes of interest then to discuss the question of whether there is a gradual transition from the state of affairs exhibited by metals in the visible spectrum to that shown well out in the infra-red, or whether this takes place largely in only a certain range of spectrum.

It has been the writer's contention² that the visible and very short infra-red spectrum is in the case of metals a region somewhat analogous to an anomalous dispersion region in the case of dielectric substances, and once wave-length about 1μ is passed we should expect to find much better agreement of theory and experiment. This conclusion was based on some experimental results³ obtained on the Kerr effect, or magnetic rotation on reflection from surfaces of the magnetic metals in a strong field. These showed, just as found by other observers, that while in the visible spectrum the dispersion of this rotation is anomalous, i.e., the rotation increases with the wave-length, when the effect is studied in the infra-red it is found to reach a maximum at $\lambda = 1 \mu$ and thereafter to decrease much as in the case of dielectric substances.

In the present work this idea meets both agreement and disagreement. Maxwell's original theory demands that, if σ is the electrical conductivity and T the period of the light-wave, then the relation should hold that $n^2 k = \sigma T$. This relation is not even approximately verified for the visible spectrum and the agreement is only a little better at $\lambda = 2 \mu$, so we must evidently go much farther into the infra-red to get rid of the disturbing influence of

¹ E. Hagen and H. Rubens, *Phil. Mag.* (6), **7**, 157, 1904; *Annalen der Physik*, **11**, 873, 1903; also see *Sitzungsberichte der Preuss. Akad. der Wiss.*, Berlin, **16**, 478, 1909.

² *Phil. Mag.* (6), **11**, 70, 1906.

³ *Ibid.*, **11**, 62, 1906.

the bound electrons, at least in so far as they affect this relation. On the other hand, in the case of reflecting powers we find a much better agreement between theory and experiment for the longer waves than for the shorter. A comparison of R as computed from the measured constants and R as observed by Hagen and Rubens shows this very well.

Kerr effect.—Voigt¹ deduces the expression for the Kerr rotation at normal incidence

$$x = \frac{|Q| \cos(q + \frac{1}{2}\pi - 2\bar{\psi})}{\sin \bar{\phi} \tan \bar{\phi}}, \quad (3)$$

where Q is a complex which does not contain n , and q is a small angle measuring the effect of the magnetic field on k . Now it is not possible at present to evaluate these two quantities for longer wave-lengths than the visible, although the writer hopes shortly to undertake some experiments which should determine directly the values of q , but it may be interesting to compare the results of this equation with experiment, on the assumption that the numerator is constant, that is, independent of the wave-length. Accordingly the following table has been made out. The figures for the Kerr rotation are an average of the writer's results,² reduced, as is $C/\sin \bar{\phi} \tan \bar{\phi}$, to unity at $\lambda = 1 \mu$.

TABLE VII

Wave-Length		0.50 μ	1.00 μ	2.00 μ
Steel	{ Kerr rotation	0.62	1.00	0.69
	{ $C/\sin \bar{\phi} \tan \bar{\phi}$	1.43	1.00	.68
Cobalt	{ Kerr rotation	0.83	1.00	.70
	{ $C/\sin \bar{\phi} \tan \bar{\phi}$	1.62	1.00	.76

As the Kerr rotation for nickel reduces to zero and changes sign at wave-length 1.5μ , such a table would mean nothing for this metal. For the other two metals it is evident that equation (3) with the above assumption represents the facts fairly well for the longer waves, but not at all for the shorter. If q had been assumed constant and the variations in $\bar{\psi}$ taken into account, the

¹ W. Voigt, *Magneto- und Elektrooptik*, p. 317. Leipzig, 1908.

² *Phil. Mag.*, **11**, 64-67, 1906.

agreement would not be quite so good. On the whole, however, this may be looked upon as an argument for the general contention that, once clear of the visible spectrum, we may expect to find a rapid improvement in the behavior of metals as regards their obedience to electromagnetic laws. That this improvement continues, though probably more slowly, out to much longer infra-red wave-lengths, the results of Hagen and Rubens' experiments show beyond a doubt.

SUMMARY

1. The optical constants of steel, cobalt, nickel, silver, copper, and silicon have been measured by a new method over the range of spectrum from $\lambda = 0.65 \mu$ to 2.25μ .

2. The first five metals show an increase of refractive index n with increasing wave-length. The absorption index k decreases in some cases and increases in others, but in general does not show nearly as much change beyond wave-length 1μ as for shorter waves. The extinction coefficient nk shows a gradual increase with the wave-length.

3. Silicon shows a slight decrease of n with increasing wave-length, much as do dielectric substances. The reflecting power also decreases, hence silicon has small right to be considered a metal optically speaking.

4. The reflecting powers computed from these constants are in good agreement with the observed values of Hagen and Rubens, especially for the longer wave-lengths. Also on certain assumptions, Voigt's equation connecting the optical constants and the Kerr rotation is fulfilled for the longer waves though not for the shorter, and these facts go to bear out the writer's contention that, once outside the visible spectrum, we may expect a much better agreement between theory and experiment in the case of the optical properties of metals.

PHYSICAL LABORATORY
UNIVERSITY OF WISCONSIN
November 1910

THE ABSORPTION SPECTRUM OF BROMINE AT HIGH TEMPERATURES

By E. J. EVANS

The absorption spectrum of bromine has been studied by Miller, Robiquet, Roscoe and Thorpe, Moser, Dale, and Hasselberg.¹ Later, Galitzin and Wilip² made an exhaustive study of the absorption spectrum at different temperatures and pressures. The most important results of their work, from the point of view of the present research, were those obtained at high temperatures, and low pressures. In some of their experiments, the quartz tube containing the vapor at a pressure of 13 mm was heated to a temperature of 1060° C., and the absorption spectrum photographed. It was found that the high-temperature spectrum was very different from the low-temperature spectrum. Some of the lines were broadened, and others were sharpened. Some lines which were very sharp and clear at low temperatures became indistinct and vanished at high temperatures, and vice versa. Also the bandlike character of the spectrum was lost at high temperatures.

Researches on the absorption spectrum of iodine have shown that the absorption lines diminish in intensity with increase of temperature, and finally disappear. The disappearance of the absorption lines at high temperatures has also been observed in the present experiments on bromine vapor, and the temperature of disappearance of the lines was found to increase as the pressure of the vapor was increased. The primary object of the research was to determine whether there is any connection between the absorption spectrum, and the state of the vapor with regard to dissociation. The temperatures of disappearance of the absorption spectrum for definite pressures were observed, and the degree of

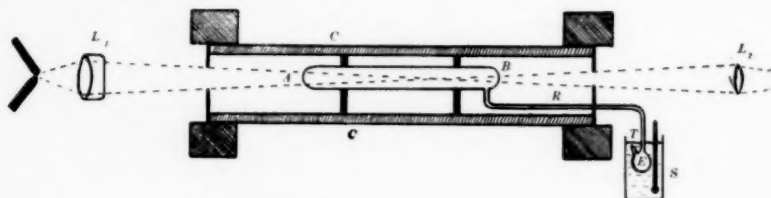
¹ Kayser's *Handbuch der Spectroscopie*, Bd. III, 320-21.

² *Mémoires de l'Académie des Sciences de St.-Petersbourg*, 17, 1-112, 1906.

dissociation for each temperature and pressure evaluated by means of the following equation due to Nernst:

$$\log \frac{1-x^2}{x^2 P} = -\frac{Q}{4.571 T} - 1.75 \log T + \Sigma \nu c.$$

In the above equation x represents the degree of dissociation, P the pressure in atmospheres, $-Q$ the heat of dissociation of the vapor, T the absolute temperature, and $\Sigma \nu c$ a constant. The values of Q and $\Sigma \nu c$ were calculated by Brill¹ from the experiments of Perman and Atkinson² on the vapor density of bromine, and found to be $-55,300$ and -1.7 respectively.



EXPERIMENTAL ARRANGEMENT

The apparatus employed in the present research was very similar to that used by the author in his investigation of the absorption spectrum of iodine at high temperatures,³ and it is necessary to give only a brief description. The bromine vapor was heated in the quartz tube AB , which was placed inside the carbon-tube electric furnace CC . By adjusting the current passing through the carbon tube CC , the temperature of the vapor could be varied from 100°C . to 1350°C . The tube AB was connected with the bulb E by means of the quartz tube R . A small quantity of pure liquid bromine was introduced into the bulb by means of the small side tube T . The bulb was kept at a temperature of -40°C ., and the side tube T connected to a Fleuss pump for evacuation. When the pressure was about 1 mm , the tube T was sealed off in the oxyhydrogen flame. To observe the absorption spectrum, the light from the positive pole of the electric arc, after passing through the large condensing lens L_1 and the vapor contained in the tube AB , was

¹ *Zeitschrift Phys. Chem.*, **57**, 721, 1907.

² *Proc. Roy. Soc.*, **66**, 10, 489, 1899.

³ *Astrophysical Journal*, **32**, 1-16, 1910.

brought to a focus on the slit of a concave grating by means of the lens L_2 . The grating had a radius of 1 meter and 15,000 lines to the inch. The first-order spectrum was always observed.

MEASUREMENT OF PRESSURE AND TEMPERATURE

The bulb containing the liquid bromine was placed in a beaker containing alcohol, and temperatures below 0° C. were obtained by dropping solid CO_2 into the liquid. The liquid was stirred, and the temperature kept constant within a degree by adding a little CO_2 from time to time. The beaker containing the alcohol was placed inside a larger vessel, and the space between them was filled with the badly conducting substance known as Kieselguhr. The bath S was always made the coldest part of the apparatus. The pressure of the bromine vapor in the tube AB was then the same as the vapor-pressure of the bromine at the temperature of the bath. Since the vapor-pressures of bromine at different temperatures were known, it was only necessary to know the temperature of the bath S to determine the pressure of the bromine vapor in the quartz tube AB . The following table taken from Galitzin and Wilip's paper (*loc. cit.*) was employed to determine the vapor-pressure of the bromine:

Temperature	Pressure	Temperature	Pressure
	mm		mm
-25° C.	8	5° C.	86
-20	15	10	110
-15	24	15	138
-10	35	20	173
-5	49	25	215
0	66	30	267

The temperature of the vapor was measured by a *Pt-Rh* thermocouple, which was connected to a galvanometer reading directly in degrees Centigrade. The couple was placed inside a quartz tube to protect it from furnace gases, and the junction was situated beyond the end A of the tube AB .

MODE OF WORK AND EXPERIMENTAL RESULTS

The experiments were carried out with the object of determining as accurately as possible the temperature at which the absorption lines completely vanished, and no detailed observations of the

changes in the appearance of particular lines at different temperatures were made. To illustrate the method of experimenting, the observations on bromine at pressures of 8.6 cm and 16 cm will be discussed. The bath temperature was kept constant at 5° C. (pressure of vapor 8.6 cm), and the temperature of the furnace was gradually raised. At first, dark bands were seen in the red, yellow, and green, and there was a general absorption in the blue and violet. The absorption in the blue and violet diminished as the temperature was raised, and when a temperature of about 1100° C. was reached there was scarcely any absorption in those regions, and the intensity of the bands in the red, yellow, and green was greatly diminished. Every trace of absorption disappeared when the temperature of the vapor had been raised to 1220° C., but on cooling, the absorption lines again made their appearance. The temperature of the bath was then raised from 5° C. to 17° C. (pressure of vapor 16 cm), and the temperature of the furnace kept at 1000° C. As the bath temperature increased, the pressure of the bromine vapor in the tube *AB* increased, and visual observations of the absorption spectrum showed that the intensity of the dark bands had also increased. The temperature at which the absorption lines vanished was found to be 1320° C. The accurate fixing of the temperature of disappearance was always difficult, as the absorption lines were very faint over a wide range of temperature. However, by keeping the eyepiece in motion during the visual observations of the spectrum, very faint absorption lines could be detected. The temperatures of disappearance of the absorption spectrum for different pressures will be found in the accompanying table.

Temperature of Bath	Temperature of Disappearance of Spectrum	Temperature of Bath	Temperature of Disappearance of Spectrum
-20° C.	830° C.	-0.8° C.	1136° C.
-15	950	+5.4	1220
-10	1030	17.8	1320
-5	1090	28	Absorption spectrum had not disappeared at 1320° C.

When the temperature of the bath was 28°C . the ends of the quartz tube became opaque, and the tube collapsed in the furnace before the absorption lines had disappeared.

EXPERIMENTS ON A CONSTANT MASS OF BROMINE VAPOR

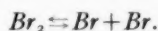
In the previous experiments the pressure of the vapor in the quartz tube was kept constant, and the absorption spectrum observed as the temperature increased. It was therefore considered desirable to investigate the effect of high temperature on the absorption spectrum when the quantity of bromine in the tube was kept constant. The bulb containing the liquid bromine was immersed in a bath of alcohol and solid CO_2 , which was kept at a temperature of -40°C ., and the apparatus was evacuated to a pressure of 1 mm. The temperature of the bath was then allowed to rise to -25°C ., and was kept constant at that value for 5 minutes. The side tube *R* near the end *B* of the quartz tube *AB* was sealed off in the oxy-hydrogen flame. The tube containing the vapor was then fixed inside the furnace, and the absorption spectrum examined as the temperature of the furnace increased. At 600°C ., absorption lines were seen in the red, yellow, and green, but they were much fainter when the temperature had reached 960°C ., and had completely vanished at 1040°C . Photographs of the spectrum were taken at the ordinary temperature of the room, and at 550° , 870° , and 1080°C . The absorption lines, which were very faint, could be distinguished in the first three photographs, but not in the photograph taken when the temperature of the furnace was 1080°C . The pressure of the vapor in the tube, when the latter was at the room temperature, was 8 mm, and it was therefore possible to calculate the pressure at 1040°C ., which was the temperature of disappearance of the absorption spectrum. The volume of the quartz tube was not much altered by heating it to a high temperature, and if it be assumed that the molecular state of the vapor was unaltered, and represented by Br_2 , the pressure was simply proportional to the absolute temperature. The calculated value of the pressure was 36 mm. Actually, the pressure was greater, because a percentage of the molecules had been dissociated. The constant pressure experiments have shown that the absorption spectrum

- disappeared at 1030° C., when the pressure of the bromine vapor was 35 mm. There is fair agreement between the results, considering the difficulty of accurately estimating the pressure at which the bromine vapor was sealed in the quartz tube *AB*.

QUANTITY OF BROMINE DETECTABLE BY ITS ABSORPTION
SPECTRUM

The bulb containing the liquid bromine was placed in the bath containing alcohol and solid CO_2 , and the absorption spectrum observed at different temperatures. At $-25^\circ C$. faint absorption lines were visible, but when a temperature of about $-33^\circ C$. was reached all traces of absorption had disappeared. The values of the vapor-pressure of bromine at temperatures below $-25^\circ C$. do not seem to have been determined, and as the knowledge of the amount of bromine detectable by the grating spectroscopy was important in the discussion of the experimental results, another method was adopted. The method employed had the advantage of determining the amount detectable at a high temperature, and also the vapor was known to be made up of a definite mixture of diatomic and monatomic molecules. The mode of procedure consisted in keeping the temperature of the bath constant at $-20^\circ C$., and raising the temperature of the furnace until the absorption lines had completely disappeared. In this way the temperature of disappearance was found to be $830^\circ C$.

The dissociation of bromine is represented by the following equation:



Let x represent the fraction of diatomic molecules dissociated, P the total pressure, and p_1 the pressure of the undissociated molecules. Then it can be shown that

$$p_1 = \frac{1-x}{1+x} P.$$

P , the total pressure of the vapor, was the same as the vapor-pressure of bromine at a temperature of $-20^\circ C$., viz., 15 mm. The fraction of dissociation x was calculated from Nernst's thermodynamic equation, and found to be 0.076. p_1 was calculated by means of the above equation, and found to be 12.9 mm.

It is therefore seen from the results of the above experiment that a pressure of 12.9 mm of the diatomic molecules can be detected. Here the assumption is made that the monatomic molecules do not contribute anything to the absorption.

The amount of diatomic bromine in the tube when the absorption lines were no longer recognizable can now be determined.

Let M = mass of bromine vapor in a tube of volume V .

Let m = molecular wt. of bromine vapor, p the pressure in dynes, and θ the absolute temperature.

Then

$$M = \frac{Vpm}{R\theta}$$

where

$$R = 8.26 \times 10^7.$$

The tube employed was 19.2 cm long and 0.512 cm in radius.

$$\therefore V = 15.8 \text{ cc}$$

$$p = 0.017 \text{ atmosphere} = 0.017 \times 10^6 \text{ dynes}$$

$$m = 160$$

$$\theta = 1103^\circ \text{ Abs.}$$

$$M = 4.7 \times 10^{-4} \text{ gr.}$$

The experiment indicated that 4.7×10^{-4} gr. of bromine vapor in the diatomic state could be detected at 830°C .

DISCUSSION OF RESULTS

To facilitate the discussion of the experimental results the following table has been constructed:

Pressure of Vapor	Temperature of Disappearance of Spectrum	Fraction of Dissociation	Fraction of Dissociation Observable by Spectroscope	Remarks
mm				
24	950° C.	0.22	0.25	
35	1030	.37	.39	
49	1090	.49	.51	
63	1136	.58	.58	
88	1220	.74	.68	
160	1320	.84	.79	
246	Spectrum had not disappeared at 1320° C.	...	...	The tube became opaque and collapsed at about 1400° C.

The third column gives the fraction of the diatomic molecules which had been dissociated at the temperature of disappearance of the absorption lines. This fraction was determined by inserting in Nernst's equation the appropriate values of the temperature and pressure. The numbers in the fourth column were deduced on the assumption that 4.73×10^{-4} grams of Br_2 molecules were necessary for the detection of the absorption lines. The pressure of the diatomic molecules present at each temperature of disappearance could readily be determined by the equation $p = \frac{MR\theta}{V_m}$, and x , the fraction of dissociation possible, evaluated by means of the relation $p = \frac{1-x}{1+x} P$, where P is the total pressure of the bromine vapor.

An error of 20° C. in the estimation of the temperature of disappearance of the absorption lines will make an appreciable difference in the calculated value of the fraction of dissociation. The following example is given as an illustration. If the absorption lines of bromine vapor at a pressure of 8.6 cm disappeared at a temperature of 1180° C., the calculated value of the fraction of dissociation would be 0.65, but if the temperature of disappearance had been 1200° C., the calculated value would have been 0.7. It is important to note that the temperatures of disappearance of the absorption spectrum for given pressures will vary with the lengths and diameters of the tubes employed. If longer tubes were employed in the above experiments, the temperatures of disappearance of the absorption lines would be correspondingly raised.

The tabulated results show that the temperature of disappearance of the absorption lines is higher the greater the pressure, and that the disappearance of the absorption is closely connected with the dissociation of the vapor. The disappearance of the absorption lines at high temperatures may be explained on the assumption that the monatomic bromine molecules give no absorption spectrum (except perhaps in very thick layers) within the range λ 3500 to λ 6800. In other words, the absorption spectrum of bromine is assigned to the diatomic molecules, and the vanishing of the absorption lines at higher temperatures is ascribed to the production of monatomic molecules, which give no absorption within the above

range. The increase in the temperature of disappearance of the absorption lines with increase of pressure is a natural consequence of the above hypothesis, for increase of pressure at constant temperature is accompanied by a diminution in the fraction of diatomic molecules dissociated.

Heated bromine vapor is known to give an emission spectrum, the lines of which coincide in position with those of the absorption spectrum. During the progress of the present work an attempt was made to observe this emission spectrum visually, but without success. In the author's paper on iodine it was pointed out that the apparatus employed in these researches was not suitable for viewing the emission spectrum, and the inability to observe the emission lines may possibly be due to the above cause.

To account for the disappearance of the absorption lines of iodine vapor, the following hypothesis has been advanced. The absorption spectrum was ascribed to the diatomic molecules, and the disappearance of the absorption lines was considered to take place when the emission due to dissociation and recombination of the iodine molecules was exactly balanced by the absorption of the iodine molecules still in the undissociated state.

The above hypothesis may possibly explain the disappearance of the absorption spectrum in the case of bromine, but it appears difficult to test it quantitatively.

SUMMARY OF RESULTS

a) The absorption spectrum of bromine disappears at high temperatures, and the temperature of disappearance is increased by increase of pressure.

b) The disappearance of the absorption lines is closely connected with the dissociation of the diatomic molecules and can be explained on the hypothesis that the monatomic molecules produced by dissociation give no absorption spectrum within the limits λ 3500 to λ 6800.

The author is indebted to Professor Rutherford and to Professor Schuster for the great interest they have taken in the work, and for placing the necessary apparatus at his disposal.

PHYSICAL LABORATORY
MANCHESTER UNIVERSITY
August 1910

MEASURES ON NINETEEN NEW SPECTROSCOPIC BINARIES

By OLIVER J. LEE

The binary character of fifteen of the stars in this article was announced in a paper by Frost and Lee read at the Cambridge meeting of the Astronomical and Astrophysical Society of America on August 17, 1910. Nothing has hitherto been published regarding the variable velocities of ι Cassiopeiae, γ Ophiuchi, and α Pegasi.

The dispersion of one prism was employed on all plates here considered, except in the case of η Coronae, for which two prisms were used for the plates designated by IIB. The usual initials have been given in specifying the observers by whom the plates were taken, viz., A=Adams; B=Barrett; F=Frost; L=Lee; M=S. A. Mitchell; S=Sullivan, who regularly assisted in the guiding.

25 σ Andromedae ($\alpha=0^h 13^m$; $\delta=+36^\circ 14'$; Mag.=4.5)

PLATE	DATE	G.M.T.	TAKEN BY	CENTER		VIOL. COMP.		RED COMP.		QUALITY
				No. Lines	Velocity	No. Lines	Velocity	No. Lines	Velocity	
IB 1198	1907 Oct. 11	18 ^h 20 ^m	B	5	km -26	5	km -59	3	km +49	g.
1719	1908 Sept. 7	17 37	B	8	+ 5					g.
1728	Sept. 8	16 14	L	5	- 6	7	-58	5	+29	v. g.
2194	1909 Nov. 25	15 16	L	7	-22					g.

g.=good; w.=weak; v.=very.

The spectrum is of type A2. The violet component was the stronger in each case where two components were measured. Metallic lines are numerous and give fairly accordant velocities.

35 Hev. ι Cassiopeiae ($\alpha=2^h 21^m$; $\delta=+66^\circ 57'$; Mag.=4.6)

Plate	Date	G.M.T.	Taken by	No. Lines	Velocity	Quality
IB 2111.....	1909 Aug. 23	18 ^h 40 ^m	F, L	12	km - 7	g.
2217.....	Dec. 22	12 15	L, B	5	+10	w.
2230.....	1910 Jan. 3	12 11	B, L	8	-21	g.
2247.....	Jan. 14	12 02	L, B	9	- 4	v. g.

This star is No. 1262 in Burnham's *General Catalogue* and is a triple star. The magnitudes are: A 4.8, B 7.0, C 8.2. The relative motion is slow and the proper motion small. The spectrum is of type A5 and has many fair lines.

$\delta 6 \rho$ Tauri ($\alpha = 4^h 28^m$; $\delta = +14^\circ 38'$; Mag. = 4.8)

PLATE	DATE	G.M.T.	TAKEN BY	CENTER		VIOL. COMP.		RED COMP.		QUALITY
				No. Lines	Velocity	No. Lines	Velocity	No. Lines	Velocity	
IB 1802	1908 Oct. 16	18 ^h 55 ^m	B, L	11	km +28	2	km -6	3	km +76	w.
1837	Nov. 8	19 57	L	8	+24	9	-22	7	+52	v. g.
1885	Dec. 4	18 34	L			7	-32	10	+63	v. g.

This star is No. 1067 of Boss's *Preliminary General Catalogue* and is a member of the "Moving Cluster in Taurus" (*Astronomical Journal*, 26, 31, 1908) for which he predicts a velocity of +41.0 km. The binary character of the star was discovered by inspection of the second plate. On No. 1885 the double lines stand out so clearly that measures of the centers were not made. The red component is the stronger on the last two plates. The spectrum is of type A5.

$\iota 8 \nu$ Geminorum ($\alpha = 6^h 23^m$; $\delta = +20^\circ 17'$; Mag. = 4.1)

Plate	Date	G.M.T.	Taken by	No. Lines	Velocity	No. Lines	Velocity H and K	Quality
IB 213....	1903 Dec. 1	22 ^h 52 ^m	F	4	km +24	2	km -6	g.
224....	Dec. 25	22 40	A	4	+33	2	+1	g.
705....	1906 Feb. 26	17 49	F	3	+6	1	+22	g.
1371....	1908 Jan. 24	17 27	B	3	+15	1	+12	g.
1947....	1909 Jan. 1	18 37	B, L	3	+20			g.

In this spectrum, of type B5, only the hydrogen lines, and one or two helium lines with H and K, are measurable. Double measures were made on No. 224 with the result +36, +30 km for the broad lines, and +4, -2 km for the calcium lines H and K. No. 1947 was too weak in the K region for measurement. The difference in velocity of the sharp Ca lines from the others is distinct and should be further investigated.

42 *Camelopardalis* ($\alpha = 6^h 41^m$; $\delta = +67^\circ 41'$; Mag. = 5.0)

PLATE	DATE	G.M.T.	TAKEN BY	CENTER		VIOL. COMP.		RED COMP.		QUALITY
				No. Lines	Velocity	No. Lines	Velocity	No. Lines	Velocity	
IB 230..	1903 Dec. 26	23 ^h 11 ^m	F	4	km + 3		km		km	g.
243..	Dec. 31	23 27	F	7	0					g.
266..	1904 Jan. 23	19 41	A	9	-17					v. g.
618..	1905 Nov. 10	22 43	B	6	+11	3	-30	3	+53	w.
961..	1907 Jan. 25	22 3	B	3	-12	4	-46	5	+27	g.

The spectrum of this star is of type B₃. Its lines are fairly distinct. The calcium lines H and K were measured on plates Nos. 243 and 266, the only two that are strong enough in the violet end. The means of accordant measures, reduced to the sun, give +17 km and +17 km, respectively, for the two plates. This suggests that the velocity for these calcium lines may not be variable.

83 ϕ *Geminorum* ($\alpha = 7^h 47^m$; $\delta = +27^\circ 1'$; Mag. = 5.0)

PLATE	DATE	G.M.T.	TAKEN BY	CENTER		VIOL. COMP.		RED COMP.		QUALITY
				No. Lines	Velocity	No. Lines	Velocity	No. Lines	Velocity	
IB 1823	1908 Nov. 2	23 ^h 14 ^m	B		km	5	km -48	6	km + 49	g.
1840	Nov. 8	23 28	L			8	+ 7	3	+103	g.
1888	Dec. 4	22 18	L	6	+16					g.

The spectral type A₂ of ϕ *Geminorum* permits of the use of a number of fairly defined metallic lines. The first two plates show such definite components that no measures were made of the centers of the lines. The appearance of the lines on the last plate suggests that they are unresolved doubles.

43 γ *Cancri* ($\alpha = 8^h 38^m$; $\delta = +21^\circ 50'$; Mag. = 4.7)

Plate	Date	G.M.T.	Taken by	No. Lines	Velocity	Quality
IB 1000.....	1907 Feb. 22	20 ^h 47 ^m	B	7	km +16	v. g.
1887.....	1908 Dec. 4	21 4	L	8	+35	v. g.
1931.....	Dec. 26	20 3	B	9	+25	v. g.
2253.....	1910 Jan. 14	17 19	B	11	+20	v. g.
2326.....	May 9	15 56	L	6	+25	g.

Some accuracy may be claimed for measures of this spectrum, classified as A. No. 1000 shows components which referred to the sun give -44 km as mean of two lines and $+42$ as mean of three. It is probable that a higher dispersion would reveal double lines.

22 θ *Hydrae* ($\alpha = 9^h 9^m$; $\delta = +2^\circ 44'$; Mag. = 3.8)

Plate	Date	G.M.T.	Taken by	No. Lines	Velocity	Quality
IB 1870.....	1908 Nov. 16	23 ^h 46 ^m	B	5	km +11	g.
1932.....	Dec. 26	20 54	B	7	+ 9	v. g.
1949.....	1909 Jan. 1	20 25	L	5	- 7	v. g.

The magnesium line λ 4481 is the best in this spectrum, of type A, and most weight was given to it. The best lines on these plates seem more or less distorted, but no consistent nor definite components have been found. Possibly they are close doubles with components of unequal intensity. The spectral lines are unusual in appearance and suggest a critical stage in the physical history of the star.

77 σ *Leonis* ($\alpha = 11^h 16^m$; $\delta = +6^\circ 35'$; Mag. = 4.1)

Plate	Date	G.M.T.	Taken by	No. Lines	Velocity	Quality
IB 317.....	1904 Apr. 16	16 ^h 45 ^m	A	11	km -11	g.
679.....	1906 Jan. 29	20 2	B	3	-13	w.
716.....	Mar. 30	17 52	F	8	-17	g.
731.....	Apr. 10	15 7	F, B	6	- 9	g.
1030.....	1907 Apr. 20	18 20	Fox	8	-12	g.
1272.....	Dec. 4	23 29	B	8	+ 4	g.
1305.....	Dec. 30	22 5	S	8	+ 4	v. g.
1309.....	1908 Jan. 6	21 49	L	8	- 2	v. g.
1315.....	Jan. 7	20 15	B	8	- 5	v. g.
1455.....	Feb. 16	19 57	L	6	-10	g.
2297.....	1910 Mar. 7	16 53	L	7	-15	v. g.

Estimates made on the earlier plates several years ago led Mr. Frost to suspect a variation in the radial velocity of this star. He also observed a suggestion of a bright line fringe to the hydrogen lines β , γ , and δ . The value -17 km for No. 716 is the mean of two independent measures, which gave -16.5 and -18.1 km. Several plates have complex lines which were not resolvable into components in measuring. The spectrum is of type A.

23 Comae Berenices ($\alpha = 12^h 30^m$; $\delta = +23^\circ 11'$; Mag. = 4.8)

PLATE	DATE	G.M.T.	TAKEN BY	CENTER		VIOL. COMP.		RED COMP.		QUALITY
				No. Lines	Velocity	No. Lines	Velocity	No. Lines	Velocity	
IB 1934	1908 Dec. 26	23 ^h 24 ^m	B	7	— 1	2	—43	2	+36	v. g.
2243	1910 Jan. 5	21 30	L	6	—23	2	—78	3	+22	g.
2306	Mar. 14	19 20	B	14	— 7			1	+46	v. g.
2328	May 9	16 45	L	6	—14					w.
2362	June 6	14 34	L	9	—16	4	—46	4	+15	v. g.

The spectrum of this star is given as A. A number of metallic lines were used in measurement. On plates Nos. 1934 and 2243 the intenser component of the magnesium line λ 4481 is on the side toward the violet, while No. 2362 has the stronger on the side toward the red. No. 2306 has traces of close double lines.

2 η Coronae ($\alpha = 15^h 19^m$; $\delta = +30^\circ 39'$; Mag. = 5.6)

Plate	Date	G.M.T.	Taken by	No. Lines	Velocity	Quality
					km	
IIB 99....	1907 Mar. 29	21 ^h 46 ^m	B	20	—12.3	v. g.
IIB 1021....	Apr. 13	20 54	Fox	13	— 8.0	v. g.
IIB 123....	May 27	15 22	F	21	—10.9	v. g.
IB 1544....	1908 Mar. 20	22 14	B	13	— 3.0	v. g.
1563....	Apr. 11	21 21	L	13	— 4.3	v. g.
1611....	May 2	19 33	B	14	— 6.2	v. g.
2383....	1910 June 20	15 7	L	7	—12.3	g.
2427....	July 18	14 48	L	9	—20.4	g.

This spectrum, of type G, has numerous good lines. The star is the well-known visual double 7251 in Burnham's *General Catalogue*. The components are 5.6 and 6.1 in magnitude. The orbit of the visual binary is fairly well determined, the period being about 42 years; hence an immediate determination of the orbit of the binary component is very desirable. A dispersion equal to that of the Bruce spectrograph with two prisms is preferable for this spectrum.

In 1902 ι *Serpentis* was found to be a close double by Hussey, who gives the distance as 0".21. It is Hu 580 or 7360 in Burnham's *General Catalogue*. The components are of equal magnitude but the following data necessitate a binary nature for one or the other

21 *Serpentis* ($\alpha = 15^h 37^m$; $\delta = +20^\circ 0'$; Mag. = 4.5)

PLATE	DATE	G.M.T.	TAKEN BY	CENTER		VIOL. COMP.		RED COMP.		QUALITY
				No. Lines	Velocity	No. Lines	Velocity	No. Lines	Velocity	
IB 758	1906 May 11	17 ^h 49 ^m	B	6	km -45		km		km +40	g.
1624	1908 May 11	18 25	L	6	-22					g.
2245	1910 Jan. 5	23 52	L			8	-30	6	+60	g.
2312	Mar. 18	20 52	L	6	-6					g.
2319	Mar. 25	20 30	L			8	-19	5	+69	g.

of the visual components. The value +40 km for the red component of No. 758 is an estimate merely of some very faint, hazy lines.

γ *Coronae* ($\alpha = 15^h 39^m$; $\delta = +26^\circ 37'$; Mag. = 3.9)

PLATE	DATE	G.M.T.	TAKEN BY	CENTER		VIOL. COMP.		RED COMP.		QUALITY
				No. Lines	Velocity	No. Lines	Velocity	No. Lines	Velocity	
IB 291	1904 Mar. 8	20 ^h 58 ^m	F	7	km +13	4	km -20		km	v. g.
1019	1907 Apr. 13	18 21	Fox	10	-14					v. g.
1044	Apr. 26	20 52	F	10	-15					v. g.
1577	1908 Apr. 13	18 28	B, L	7	-8	5	-53	3	+29	g.
2321	1910 May 6	16 45	B	8	-17					v. w.
2428	July 18	15 52	L	4	-26	6	-80	6	+26	v. g.
2441	July 25	14 6	L	10	-23					v. g.

This is the close visual double star No. 7368 of Burnham's *General Catalogue*. See (*Evolution of the Stellar Systems*) gives its period as 73 years and its semi-major axis as 0".736, the plane of its orbit lying almost in the line of sight. The fainter component is of the 7th magnitude. The spectrum of the brighter component is classified as A, although the metallic lines are numerous and permit of considerable accuracy in measurement. When the spectroscopic components are visible they are of equal intensity. As in the case of η *Coronae*, an early determination of the orbit is desirable.

The spectrum of π *Serpentis* is classified as A2. Numerous metallic lines were used in measuring velocities. Peculiarly, the violet component seemed the more intense on all the plates. The

44 π *Serpentis* ($\alpha = 15^h 58^m$; $\delta = +23^\circ 5'$; Mag. = 4.8)

PLATE	DATE	G.M.T.	TAKEN BY	VIOL. COMP.		RED COMP.		QUALITY
				No. Lines	Velocity	No. Lines	Velocity	
IB 1995....	1909 Mar. 1	21 ^h 15 ^m	L	12	km -41	3	km +35	v. g.
2270....	1910 Jan. 21	23 40	L	10	-15	2	+69	g.
2299....	Mar. 7	19 47	B	10	-62	10	+29	v. g.
2365....	June 6	17 22	L	8	-48	6	+38	v. g.

components were so definite that no attention was given to measurements of the centers of the lines.

62 γ *Ophiuchi* ($\alpha = 17^h 43^m$; $\delta = +2^\circ 45'$; Mag. = 3.7)

Plate	Date	G.M.T.	Taken by	No. Lines	Velocity	Quality
IB 721....	1906 Mar. 30	22 ^h 40 ^m	B	4	km + 2	v. g.
1095....	1907 June 29	19 19	Fox	5	+11	g.
1098....	July 1	16 0	B	8	-19	g.
2314....	1910 Mar. 18	22 51	L	6	+35	v. g.
2358....	May 30	19 59	B	8	+ 4	g.
2410....	July 1	16 7	B	7	- 9	g.
2416....	July 4	17 8	B	8	- 4	g.

The binary character of this star was early suspected by Mr. Frost. No. 721 shows five lines resolved into measurable components, the resulting velocities for which are -51 km and +92 km. The spectrum is of type A.

27 ϕ *Sagittarii* ($\alpha = 18^h 39^m$; $\delta = -27^\circ 6'$; Mag. = 3.3)

Plate	Date	G.M.T.	Taken by	No. Lines	Velocity	Quality
IB 38....	1903 June 6	20 ^h 19 ^m	A	1	km +20	v. w.
362....	1904 June 11	18 48	F, B	9	- 2	v. g.
1680....	1908 Aug. 17	15 49	F, B	8	+39	g.
1685....	Aug. 21	13 54	L	8	+32	v. g.
1690....	Aug. 24	14 6	B	7	+26	v. g.
1699....	Aug. 25	14 31	L	7	+32	v. g.
1708....	Aug. 28	14 49	L	7	+36	g.
2021....	1909 May 17	20 26	B	10	+17	v. g.
2436....	1910 July 19	16 38	L	9	+34	v. g.

Mr. Frost on the basis of his preliminary measures announced ϕ *Sagittarii* as a spectroscopic binary at the meeting of the American Astronomical and Astrophysical Society at Put-in-Bay in 1908. This meeting was reported in *Science* for December 11, 1908. The individual measures have not before been published. The spectrum is of type B5A.

13 *Vulpeculae* ($\alpha = 19^h 49^m$; $\delta = +23^\circ 49'$; Mag. = 4.5)

Plate	Date	G.M.T.	Taken by	No. Lines	Velocity	Quality
					km	
IB 761.....	1906 May 11	20 ^h 58 ^m	F	8	-27	v. g.
2015.....	1909 May 10	21 38	B	9	-35	v. g.
2028.....	May 24	19 5	B	3	-15	w.
2054.....	June 18	17 16	M	8	-30	v. g.
2348.....	1910 May 23	21 10	B	9	-36	v. g.
2374.....	June 10	19 46	L	8	-36	g.
2406.....	June 27	18 25	L, M	8	-15	g.
2430.....	July 18	18 20	L, B	10	-26	v. g.

The spectrum of this star is of type A with a number of fairly sharp metallic lines. On No. 2054 the best two lines measured each have a faint component. The mean, referred to the sun, gives +119 km. No. 2406 also shows components at -51 km from four lines and +12 km from three lines.

16 *Lacertae* ($\alpha = 22^h 52^m$; $\delta = +41^\circ 4'$; Mag. = 5.5)

Plate	Date	G.M.T.	Taken by	No. Lines	Velocity	Quality
					km	
IB 2110.....	1909 Aug. 23	17 ^h 1 ^m	F	9	-43	g.
2178.....	Nov. 8	16 42	L	10	+12	g.

The spectrum is B3 and has many fairly good lines. On plate No. 2178 two lines show well two components, giving velocities of -12 km and +45 km. The *Ca* lines H and K are sharp, and accordant measures of the two give -15 km and -17 km, respectively, for the two plates. This indicates that the star may belong to the class of binaries having a constant velocity for *Ca* lines.

α Pegasi ($\alpha = 23^{\text{h}} 0^{\text{m}}; \delta = +14^{\circ} 40'; \text{Mag.} = 2.6$)

PLATE	DATE	G. M. T.	TAKEN BY	CENTER		VIOL. COMP.		RED COMP.		QUALITY
				No. Lines	Velocity	No. Lines	Velocity	No. Lines	Velocity	
					km		km		km	
IB 2420	1910 July 4	21 ^h 39 ^m	L			9	-24	4	+61	v. g.
2425	July 8	21 38	L	7	+13					g.
2460	Aug. 1	17 56	L	5	-3					g.
2469	Aug. 5	20 18	L	7	+9	2	-24	2	+60	v. g.
2474	Aug. 8	17 51	L	7	+28	1	-24	2	+80	v. g.
2480	Aug. 12	17 40	B	5	-1					v. g.
2488	Aug. 19	16 5	B	5	-3	2	-30	2	+54	v. g.
2491	Aug. 25	16 30	B	4	-2					v. g.
2499	Aug. 27	16 48	L	6	-7					v. g.
2501	Sept. 12	15 54	L	6	-2					v. g.

α Pegasi has a spectrum of type A. Metallic lines are faintly present, but few are of any value for measurement. The K line of calcium has a peculiarly distorted double appearance, without showing measurable components, however, except on the first plate. Most of the spectrograms of this star were made on "Seed 23" plates.

YERKES OBSERVATORY

September 30, 1910

THE ABSORPTION IN THE RED OF THE ACETATE, NITRATE, AND SULPHATE OF COBALT

By FRANK L. COOPER

INTRODUCTION

In a previous number of this *Journal*,¹ the writer published the results of an investigation on "The Absorption of Certain Salts in Aqueous and Non-aqueous Solutions." In this work the absorption spectra of several salts of cobalt, copper, iron, and neodymium were examined, and from the evidence obtained, the following conclusions were reached:

1. The absorption of light by the solutions studied was due to at least two different kinds of absorbers, one of which was the molecule of the salt, and another the atom of the metal itself.
2. The absorption spectra of these salts in solution depend to a great extent upon the solvent, which probably forms some simple hydrate.

It was observed that in the case of the solutions of cobalt bromide, cobalt chloride, and cobalt iodide several narrow absorption bands in the red region of the spectrum were characteristic of each salt; while the red was almost entirely transmitted by salts having oxygen as a part of the radical. In the more concentrated solutions of cobalt nitrate and cobalt sulphate, however, there appeared to be an absorption band which approached from the infra-red and absorbed a little of the light in the extreme red. For this reason, the present work was undertaken, using solutions of greater concentrations than those which were used in the previous work, to ascertain whether there were absorption bands which approached the visible spectrum from the infra-red, and whether these were also characteristic of the salt solution used.

APPARATUS, MATERIAL, ETC.

The spectrograph employed for this work was the same instrument which was used in the previous investigation. It consisted of a plane Rowland grating of about 14,000 lines to the inch which

¹ *Astrophysical Journal*, 31, 4, 1910.

was mounted in a light-tight box. The absorption spectrum of each solution was also carefully examined by means of the small spectroscope. Both of these instruments were described in the previous paper. There were two cells used, so that the length of the absorbing layer was either 2 cm or 4 cm. The photographic plates were "spectrum panchromatic plates" obtained from Wratten and Wainwright of Croydon, England, and were sensitive as far as λ 8000 and very sensitive to about λ 7600. The plates were developed with dianol developer obtained from the Lumière Company.

The source of light was a 220 volt direct-current Nernst lamp carrying a current of 0.5 ampere, a variable resistance being also placed in the circuit to maintain a constant current. For comparison, the spectrum of the iron arc with Norway iron electrodes was used.

The solutions were made up in the same manner as those used in the previous work. A chosen volume of mother-solution of a colored salt was measured out from a burette into a measuring flask of known capacity. The portion of the solution in the flask was then diluted by the addition of pure water until the volume of the resulting homogeneous liquid was exactly equal to the fixed capacity of the flask. The concentrations will always be expressed as multiples of normal. The term normal will be used to mean gram-molecular normal.

Through the courtesy of Professor J. S. Ames of the Johns Hopkins University, it was possible to measure the plates with the dividing engine belonging to the physical laboratory of that institution. This engine is fully described by Humphreys in the *Astrophysical Journal*, 6, 180, 1897.

METHOD OF INVESTIGATION

The light from the Nernst lamps was allowed to pass through the cell containing the absorbing solution, and focused upon the slit of the spectrograph. After reflection from the grating, it was brought to a focus at the camera box.

Spectrograms were made both when aqueous and also amyl alcohol solutions of the salts were used as the absorbing media. The results were also verified by visual observations.

RESULTS

Aqueous solutions.—Solutions of the acetate, nitrate, and sulphate of cobalt were studied, the concentration of the solutions increasing from two-normal. In every case, it was found that with increasing concentration of the solution the absorption band in the green always approached the red end of the spectrum, as had been observed in the previous work. Moreover, in each case there was always an absorption band which slowly widened, coming from the infra-red, and gradually absorbed the lower part of the red region of the spectrum. These red absorption bands moved much more slowly, however, than did the band in the green, especially in the case of the more dilute solutions. The position of these absorption bands differs according to the salt solution used as the absorbing medium, but the exact position of their center could not be determined photographically, as they are in the infra-red. In the case of each of the solutions studied, the red absorption bands widen very slowly if the solution is dilute, but quite rapidly with solutions of greater concentration. Similar results were previously found in the case of solutions of cobalt bromide, cobalt chloride, and cobalt iodide. Therefore it is quite probable that these absorption bands are very similar to the red absorption bands of the bromide, chloride, and iodide of cobalt, and that the reason that they differ in position for different salts is because the absorber which is responsible for their existence is the molecule of the salt. On the other hand, the absorption band in the green was always found to begin in about the same position in the spectrum, about λ 5200, which is what we would expect if the absorber which produced this band was the atom of the metal itself. The width of this absorption band increased most rapidly, with increase of concentration, in the case of cobalt acetate, and least rapidly when a solution of cobalt nitrate was used as the absorbing medium. This shows that the absorber which is responsible for the green band cannot be the cobalt cation. Arranged in order of increasing dissociation, the salts would be acetate, sulphate, and nitrate. If the absorber responsible for the green band had been the cobalt cation, then this band should have been broadest in the case of the solutions in which there was the most dissociation, i.e., the solution of cobalt nitrate.

Below is given the approximate position of the limit of transmission for the green absorption band, in the case of a three-normal solution of the different salts studied:

Cobalt nitrate, λ 5725

Cobalt sulphate, λ 5850

Cobalt acetate, λ 6150

The limits of transmission in the red corresponding to the above were approximately

Cobalt nitrate, λ 7450

Cobalt sulphate, λ 7340

Cobalt acetate, λ 7270

Alcoholic solutions.—The absorption spectra of cobalt acetate, cobalt nitrate, and cobalt sulphate, when dissolved in amyl alcohol, were also studied. All of these, like the aqueous solutions of these salts, were found to have absorption bands both in the green and the infra-red. It should be stated, however, that some of the salts were not absolutely anhydrous. The positions of these bands were not the same as those in the case of the water solutions, as was found in the case of the ethyl and methyl alcohol solutions. This therefore confirms the conclusion that, in the solution, there is probably formed some simple solvate.

Below is given the limit of transmission in the red, as the concentration of the amyl alcohol solution of cobalt nitrate was increased by equal amounts as far as saturation:

λ 7380 λ 7279

λ 7360 λ 7212

λ 7329 λ 7109

λ 7312 λ 7014

SUMMARY

The results obtained with the solutions of cobalt acetate, cobalt nitrate, and cobalt sulphate confirm the conclusions reached from the previous work, viz.:

1. The absorption of light by the solutions studied was due to at least two different kinds of absorbers, one of which was the molecule and another the atom.
2. The absorption spectra of these salts in solution depend to a great extent upon the solvent, which probably forms some simple solvate.

SHEFFIELD SCIENTIFIC SCHOOL
YALE UNIVERSITY
November 1910

1940



GIOVANNI VIRGINIO SCHIAPARELLI

MINOR CONTRIBUTIONS AND NOTES

GIOVANNI VIRGINIO SCHIAPARELLI

G. V. Schiaparelli was born in Savigliano (province of Cuneo in Piedmont) on March 14, 1835. Beginning his studies in Savigliano, he continued them in Turin, where he followed the courses in civil engineering, taking the degree in 1854. In the two following years Schiaparelli taught mathematics, and studied modern languages and astronomy. He felt greatly attracted to this science and was not diverted from it, although favorable opportunities in another kind of work were opened to him by someone who had discovered in the youth of twenty years an extraordinary talent, strong purpose, noble ideas, and faith in their possible execution, which led later on to great achievements. In 1857 the government of Piedmont sent him to study astronomy in Berlin and Pulkowa under Encke, O. Struve, and Winnecke. There he spent three years in researches in theoretical and practical astronomy, as well as in various other branches of science, as mathematics, geography, and physics. In 1860 he was called as second astronomer to the Observatory of Brera in Milan, and two years later succeeded Francesco Carlini as director. He remained in charge until 1900, when, after forty years of service, he asked to be retired. Thereafter he lived privately in Milan, until his death on July 4, 1910.

From this bare description of the life of Schiaparelli we see that two periods are prominent: one, of twenty-five years, from 1835 to 1860; the other, of fifty years, from 1860 to 1910. In the first, the man grows, studies, and prepares himself for life; in the second, he works up to his last breath, without a rest, and always for science. The history of the first forty years of this second period has been recorded by thirty-six Italian astronomers in the quarto memoir of 86 pages issued in 1900 on the occasion of his retirement from the observatory, and bearing the title, *All' Astronomo G. V. Schiaparelli—Omaggio—30 Giugno 1860—30 Giugno*

1900. The activity of the great astronomer during the forty years is well described in that publication, which gives for each year a list of his numerous contributions to science (in all, 236 numbers). The esteem in which he was held by his contemporaries is sufficiently indicated by the enumeration there given of the forty-eight learned societies which made him their associate and by the honorary degrees conferred upon him.

It is hard to believe that the lifetime of one man was sufficient to give the world all the various scientific productions of Schiaparelli. These are perfected in each detail, as condensed in thought as Latin classics, elegant in form, clear as to formulae and tables, neat as to drawings, easy and smooth in style. A single year of his activity would be enough to make an astronomer famous; and not only an astronomer, but also a geodesist, meteorologist, historian, or mathematician.

Entering as astronomer in Milan and having old instruments, the equatorial sector of Sisson and the meridian circle of Starke, each with a telescope of four inches, he discovers with the first the sixty-ninth asteroid, *Esperia*, and observes with the second the stars of the zone $+6^{\circ}$ and -2° of declination, before the *Astronomische Gesellschaft* had been organized for the observations of all zones of Argelander. He does not stop at his observations, but reduces and computes them, reaching results that increase our astronomical patrimony. In this way we have now the translation of the classic memoir of Encke on the determination of an elliptical orbit with three observations, and the star-catalogue for the equinox of 1870 observed and reduced by him and his successor, Giovanni Celoria (*Publications of Brera*, No. XLI).

The young astronomer was already well known in 1862, in spite of his great modesty and retired life. The clever men who at this time ruled, not only over little Piedmont, but also over new Italy, recognized the worth of the man and provided him with a better instrument, the well-known equatorial of Merz, 8 inches in aperture. Schiaparelli tries the instrument on *Mars* in 1877, and lays out great programs of work, all of which he accomplishes. Hence we have today in the first five memoirs on *Mars* printed in the *Lincei* and in his measures of double stars in the *Publications of*

Brera, No. XXXIII, a permanent memorial, increasing the field of knowledge in physical astronomy and in the astronomy of position. While accumulating observations at every moment of the clear nights, never resting; while he is preparing the material for future works, almost fearing the want of stones for his great edifice in the field of practical astronomy, he writes the famous letters to Father Secchi, and concludes his theory on the shooting stars which made his name famous. And he writes, almost as a relaxation from his persistent observing: *I precursori di Copernico nell' Antichità*, and *Le sfere omocentriche di Eudosso, di Callippo e di Aristotele*. He divines and proves the cosmical origin of meteors and their connection with the comets, giving a splendid demonstration of the genesis of meteoric swarms from the disaggregation of the comets. To the ancient Greek school he ascribed the first honor of the heliocentric hypothesis. He also corrects the view as to the homocentric spheres which had not been understood by the historians, whose knowledge of mathematics and language was not sufficient to explain those ideas, so that in ridicule they made of them the famous crystalline spheres.

Despite this great intellectual activity, Schiaparelli keeps in touch with the world and advances with it, finding joy in his family life and in the education of his sons. He maintains close association with his colleagues, with the academies, and with the famous men of his time, such as Secchi, Struve, Dembowski, Donati, De Gasparis, and Baeyer. With the last named, and with other members of the International Geodetic Association (of which he became a member in 1864) he co-operates for the advancement of the geodetic survey. His help and advice are freely accorded to all. W. Tempel is given a position in his observatory and then sent to Arcetri; Father Denza receives his effective co-operation in his propaganda for cosmic meteorology; the Observatory of Padua obtains the equatorial of Dembowski; Antonio Favaro has Schiaparelli as consulting co-operator in the national edition of the *Opere di Galileo Galilei*; C. A. Nallino, with the help of the Brera Observatory, is sent to the Escorial to copy in that library the only existing Arabic text of Al-Battānī, which copy is then printed in No. XL of the *Publications of Brera*.

Examples like these could be multiplied in great number. His latest service was given to the new Italian Astronomical Society, especially when the worthy astronomer of Teramo became its president. It is with emotion that we read his last work (the life of Ignazio Porro) in the *Review* of the society, in the number for July of this year. In the last days of May, while sending it to Vincenzo Cerulli, he foresees his end, and writes to him:

A me preme di mostrare col fatto che, malgrado il mio stato di crescente infermità, io conservo sempre il desiderio di far cosa grata a Lei ed utile alla Rivista. Caro amico, questa orribile primavera mi ha assassinato: i miei acciacchi crescono: ai vecchi se ne aggiungono di nuovi: presto verrà per me il tempo di dire: Fuimus Troës. . . .

To the skilful direction of Schiaparelli we owe collective works worthy of the greatest observatory, endowed with much more means than the one of Brera: for instance, the *Effemeridi astronomiche di Milano*, which were abandoned for the sake of other publications such as the *Pubblicazioni del Reale Osservatorio di Brera in Milano*, which began in 1873. With this great and continuous program are connected many special researches which, presented modestly before academies, or in scientific and popular reviews, treat of new facts deduced from his observations. Such are the rotation of *Mercury* and *Venus* in times equal to their sidereal revolution, the appearances of the rings of *Saturn*, the ellipticity of *Uranus*; or he writes to oppose wrong interpretations of phenomena which have not actually happened, as the change in color of *Sirius*, concerning which he sent to the Academy of Rovereto in 1896-1897 the two classic papers entitled "*Rubra canicula*."

Let us go back to his observatory in 1878 and we shall see that Schiaparelli, already made famous by his researches with the 8-inch telescope, asked the Italian government for the means for purchasing a more powerful instrument. His wish was hardly expressed before he obtained the approval by King Humbert of the act under which the Senate and the Chamber proposed to purchase and place in the Observatory of Brera a refractor of 18 inches aperture. The new instrument arrives in Milan in 1882, but difficulty in the construction of the dome delays the use

of it until 1886, fourteen years before Schiaparelli leaves the observatory. The history of fourteen years of observations with the great Merz-Repsold refractor is recorded in two memoirs of the *Lincei* on *Mars*, the last of which has just now been published in 1910, and in the volume on double stars which is publication No. XLVI of Brera, for the year 1909. For many of the most interesting binaries the measures are repeated year after year, so that we have a valuable and almost continuous record, made by a single observer, through a considerable length of time, of the motion of those systems. The close of the introduction to this work reveals once more the man. There he remembers the help given to him for this publication with brotherly benevolence by his friend and colleague, G. Celoria, and calls Otto Struve and Ercole Dembowski his masters in the subject of double stars.

Schiaparelli's broad interest in humanity is illustrated by the following quotation from one of his letters, written in 1900:

Science, which is now only in its beginning, has already brought many material benefits to humanity, but much greater will be the measure of all the good that it will be able to procure, especially for moral progress.

The life of the indefatigable man is declining, his sight is weakening, more and more, and he is obliged to discontinue observing, but still he does not rest after his retirement from official life. His broad culture is again emphasized when he writes in the *Manuali Hoepli* the history of the Hebrew astronomy ("L'astronomia nell' antico Testamento"), discussing the original texts written in that language. From the Arabians, Greeks, and Hebrews he goes to the Babylonians and writes for the review *Scientia* (1908) the two studies: "I primordi dell' astronomia presso i Babilonesi" and "I progressi dell' astronomia presso i Babilonesi." Remarkable is the conclusion of this last article, which condenses in few words the astronomical history of twenty-five centuries, from 600 B.C. to the present day. He writes:

Concluding briefly, we will say that the true merit of the Babylonians was to establish in empirical form, with continuous observations and with the art of computing, the first basis of scientific astronomy. Starting from this point, the Grecians created geometrical astronomy, that is, the description of the arrangement and forms of the celestial movements. This found its cul-

mination and perfection in Copernicus and Kepler; after which Newton, starting from Galileo's principles of mechanics, showed how to deduce all the laws of these movements from the one physical cause, gravitation. This mechanical astronomy seems to have reached its highest point in regard to principles; but in the application there is a long way to go yet, since we have to study not only the planetary system, but also all the stellar systems: a formidable problem, the first lines of which are only now beginning to be laid down.

To this third stadium recently a fourth one has been connected—astrophysics. . . .

Schiaparelli felt intuitively the great importance of this branch of astronomy, and although it was impossible for him, owing to his advanced age, to take an active part in its development, still he followed with the greatest interest the rapid progress of the new science. In his last days he spoke with enthusiasm of the new and powerful developments in his beloved science, especially appreciating the work of American astronomers, and admiring not only the great facilities they secured, but also the tenacity of their scientific purpose in making these powerful means effective.

Schiaparelli appreciated highly the visit made by Mr. Hale at his house in Via Fatebenefratelli, just about a year ago.

Honors and prizes were never sought by Schiaparelli, but he nevertheless received many of them. But so far as he was concerned, they would be unknown to others, since he thought he did not deserve them, holding it to be his duty to do all in his power without expecting any other reward. "Omni enim habenti dabitur" (Matt. 25:29). He had numerous civil, national, and foreign honors. He was made senator of the Kingdom of Italy in 1889, but he was not sworn in until nine years later, since he could not reconcile himself to the idea that he should have to make laws for men, while he was accustomed to say: "I know only very little those of the skies!" Three gold medals (Italian, English, and German) and two Lalande prizes from the Institut de France, in 1868, 1872, 1876, and in 1890, attest to the esteem in which he was held by his contemporaries. Another evidence of this was shown in the anxiety felt by the whole intellectual world during

his short sickness, indicated by the Italian and foreign newspapers of the first days of last July. On the morning of July 4 his soul left his frail body: "*Spiritus ubi vult spirat, et vocem ejus audis*" (John 3:8). We hear and shall continue to hear his voice in his works.

He died on a day of brilliant sunshine, at a short distance from the Observatory of Brera, which he had made famous. He seemed to sleep in sweet resignation among his sons, relatives, and friends, in his bright and quiet room. The funeral services were simple, as requested by the deceased, who had no taste for ostentation, but they were solemn for the company of distinguished men of Milan and elsewhere, and for people of all classes. Now his mortal remains lie in a secluded place in the cemetery of Milan, but his spirit is sufficient to keep the mind of the learned world awake: he lives forever.

A.

ON THE TEMPERATURES OF STARS

The good feeling with which Professor Wilsing writes relating to my criticisms of the work of Wilsing and Scheiner, and the important corrections which he has determined, which go so far toward reconciling certain discrepancies, have pleased and interested me greatly. I am emboldened to venture a little farther, however, taking as my text the following quotation from Professor Wilsing: "From Mr. Abbot's remark, 'It seems misleading to compute temperatures from a spectral range of only 0.2μ ,' it would seem that he has not considered the form of the equations of condition from which the temperatures are determined."

I had less in mind the mathematics of the matter than the march of the sun's energy-curve. Suppose that one observer should use photographic methods and determine by observations at five wave-lengths the form of the sun's energy-curve outside the atmosphere from $\lambda=0.3 \mu$ to $\lambda=0.5 \mu$, and another should use visual methods and determine it from $\lambda=0.5 \mu$ to $\lambda=0.7 \mu$. Let us suppose further that the results of each observer should agree with the mean results of our bolometric work on Mount Wilson and Mount Whitney, which I take roughly as follows from

a curve to be given in a book on *The Sun* which I hope will be soon forthcoming:

Wave-length.....	μ 0.30	μ 0.35	μ 0.40	μ 0.45	μ 0.50	μ 0.55	μ 0.60	μ 0.65	μ 0.70
Intensity.....	11.2	113	167	216	210	195	177	157	130

The supposed two investigators might proceed to determine the solar temperature by the formula

$$\log \frac{E_1}{E_2} = -5 \log \frac{\lambda_1}{\lambda_2} - \frac{c \log e \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right)}{T}$$

according to the method of least squares.

If I make no error their results would be (for $c = 14,200$) $T = 3932^\circ$ and $T = 6900^\circ$, respectively. If the first observer should reject the observation at 0.30μ and the second should reject the observation at 0.70μ the results would be $T = 5142^\circ$ and $T = 7056^\circ$, respectively.

Keeping all the observations, the results differ by about 3000° , and keeping four of each set, they differ by about 2000° . In either case the divergence seems very large.

Professor Wilsing will perhaps rejoin that the first observer should have known better than to take his observations in a region full of Fraunhofer lines, and so, of course, he should. But if the sun had been a star of the third or fourth type, would not the second observer or even one observing from $\lambda = 0.45 \mu$ to $\lambda = 0.65 \mu$ encounter the same difficulty? On the other hand, do we know that the energy-spectra of stars of the first type are free from peculiarities of a similar tendency, though not of a similar cause? In other words, can we be sure that the region of spectrum $\lambda = 0.45 \mu$ to $\lambda = 0.65 \mu$ may be assumed typical of their general energy-distribution, so that it may serve to indicate their approximate temperatures? Indeed, may not the stars of the second type itself differ so much in the effects of their selective absorption and general scattering that in many of them the energy-distribution from $\lambda = 0.45 \mu$ to $\lambda = 0.65 \mu$ gives a false view of their temperatures?

It is with considerations like these in mind that I am led to believe that we shall do well to mistranslate the title of the valuable work of Wilsing and Scheiner, and to read "Determination of the

Spectral Distribution of the Visible Radiation" rather than "Temperature Determination."

C. G. ABBOT

SMITHSONIAN STATION
MOUNT WILSON, CAL.
October 21, 1910

NOTE ON BELL'S PAPER ON STAR COLORS

I have read Mr. Louis Bell's paper entitled "Star Colors: A Study in Physiological Optics," in your issue of April last (31, 234-257, 1910).

It is true that in the first half of the last century, several double-star observers were fantastic in assigning colors to double stars; W. Struve and Smyth being perhaps the most so. The greater number of modern observers, including Burnham, Hussey, and Aitken, are most sparing in noting the colors of double stars. Thus the excess of fancy to which Mr. Bell justly objects is not a fault of today. Still, I venture to believe that the astronomer should record the colors of the stars he observes, but only on the modest "Chandler" scale varying from white (steely bluish) through yellow and orange to red, adding "b" for bluish and "B" for quite blue. It is probable enough that whenever "b" or "B" has been used by myself a subjective effect is present. I have never swept upon nor seen a decidedly blue, purple, or green isolated star. White (or what many people call steely blue), yellow, orange, and red, or mixtures thereof, are the only colors so found. To Mr. Bell's laboratory experiments we can add a celestial one which was produced by the near approach of the ruddy *Mars* to the yellow binary γ *Virginis* in March 1903. *Mars* was then 4 or 5 on Chandler's scale, γ *Virginis* was decidedly bluish (see *Cape Annals*, 2, p. xc).

But all the cases presented by double stars will not fit in with a purely subjective theory. In the great cluster around α *Carinae* (the finest coarse cluster in the sky) there is one exceedingly red star and several yellowish stars, but there are no bluish or blue stars whatever. In the great cluster Δ 597 *Scorpii*, there are some yellow stars, but no bluish or blue stars. Thus, although a contrast of color is present in both cases, it leads to nothing. In

the pair *a Centauri*, the brighter star is quite yellow, the fainter star is, however, yellower, and this is only a typical case. The pair *a Circini* has been described as follows:

	Bright Star	Faint Star
J. Herschel	White	Yellow
Russell	Faint Yellow	Orange
Innes	2 (yellowish)	7½ (decidedly reddish)

The 6'' faint companion to χ_3 *Fornacis* is an orange-red star. Again, many stars quite yellow have companions which are only slightly bluish, while some nearly white stars have very blue companions; thus the 5'' pair *h* 3891 has a white primary with a tinge of yellow, while the smaller star is decidedly blue.

R. T. A. INNES

TRANSVAAL OBSERVATORY
September 13, 1910

REVIEWS

The Scientific Papers of Sir William Huggins. Edited by SIR WILLIAM AND LADY HUGGINS. London: William Wesley & Sons, 1909. Quarto. Pp. xii+539, with photogravure portraits and many illustrations. 30s.

The publication of this splendid volume is justly a ground of general congratulation: to the distinguished author and his efficient coadjutor, that they have been permitted¹ to arrange in an appropriate, permanent manner these records of the devotion of a lifetime to science; to present and future workers in the field, that these pioneer researches of astrophysics are available for the consultation and study which their fundamental quality and historical importance will always require. The subtitle, "Publications of Sir William Huggins's Observatory, Vol. II," relates the work properly to its preceding volume, published ten years ago, *An Atlas of Representative Stellar Spectra from λ 4870 to λ 3300, Together with a Discussion of the Evolutional Order of the Stars, and the Interpretation of Their Spectra.*² That volume laid especial emphasis upon the reproductions of the spectra, many of them classical, and their discussion; this collects the published papers on the work done at the observatory in the half-century since its foundation in 1856. The papers are arranged by subjects, in eleven sections, generally following chronological order under each section. All the papers are reprinted as they appeared, in full, without alteration or omission. In some cases, where it appeared desirable to the editors, short notes are added. These, it is hardly necessary to say, lend an increased value to the original statements. The topics of the sections are as follows: I, Observatory and Instruments, 32 pp.; II, Spectra of the Fixed Stars, 68 pp.; III, Spectra of Nebulae, 90 pp.; IV, Motion in the Line of Sight, 41 pp.; V, New or Temporary Stars, 25 pp.; VI, Spectra of Comets, 39 pp.; VII, Sun and Corona, 54 pp.; VIII, Moon, Planets, and Aurora, 38 pp.; IX, Chemical Spectra, 64 pp.; X, Miscellaneous, 20 pp.; XI, Lectures and Addresses, 60 pp.

With this great range of research in new fields, it is not easy to select

¹ Written before the lamented decease of Sir William.

² Also published by Wesley. Folio, cloth. Price £1:5s., net.

the chapters of greatest appeal and importance. The line of the reader's own work or interest will be to some extent controlling. It is evident that there is fundamental matter enough to cover most of the field of astrophysics. The very quality of the book makes it especially difficult to review, for the fascination of reading and re-reading some of these classical expositions of the progress of investigations in these unexplored regions of knowledge precludes the use of the reviewer's pen.

However, the chapters on the application of spectroscopy to the nebulae, to the fixed stars, and to the sun, and that on motion in the line of sight, record the most significant of the Huggins' discoveries. There is a temptation to quote liberally from them, but that would involve far too much space: one would scarcely know how to stop. The volume should be read by all who are at work in this field, and in its borderlands physicists and chemists will find much to attract and interest them. The charm of the lectures and addresses will appeal to all caring for the history of science, but not desiring to follow all the details of the original papers.

There is a fine spirit of patience and calmness throughout the work of the author. He does not rush into print to anticipate his contemporaries. Thus twelve years intervene between the paper "On the Spectra of Some of the Fixed Stars" (in collaboration with Dr. W. A. Miller), 1864, and the first paper "On the Photographic Spectra of Stars," 1876. Part II of this last does not appear until 1880. He has meanwhile been working on the spectra of nebulae and other objects, of course; but his method is inductive, built upon personal observations slowly, painstakingly but not painfully, gathered with what now would be considered wholly inadequate instruments, in an unfavorable climate. We of the present day would consider it almost hopeless to derive positive information from the visual study of the feeble, flickering band of spectrum produced by a small spectroscope attached to an eight-inch refractor.

Sir William Huggins was always alert for new developments by other workers in his special science and its cognate branches, physics and chemistry; and his application of such new findings was always keen. His position in regard to his contemporaries was frank and generous, and rarely controversial. He frequently felt it necessary, however, to test by the most precise possible measurements the deductions of one of his fellow-pioneers, whose genius at times leaped the barriers of direct demonstration and found confirmation of theories in data of insufficient accuracy.

The volume is illustrated with the diagrams and maps accompany-

ing the original papers, and is greatly embellished by excellent photographs of the two authors.

The printing is excellent, as would be expected. The volume unfortunately could not well be made to match the style of Vol. I, which had to be larger to include on a sufficient scale the many reproductions of plates of spectra. But the series of publications of the Tulse Hill Observatory ends with these two noble books, which record in conveniently accessible, permanent form the original statements of some of the greatest advances in astronomy of the nineteenth century.

The teacher whose time may be too fully occupied with classroom work, or whose equipment may seem too meager, for personal work in research will derive from the repeated study of these volumes a new inspiration for his efforts, which cannot fail to impress his students afresh with the marvel of the revelations of the spectroscope in its astronomical applications.

E. B. F.

Acht Vorlesungen über theoretische Physik. Von MAX PLANCK.
Leipzig: S. Hirzel, 1910. 8vo, pp. 127, figs. 5. M. 3.60;
bound, M. 4.20.

Die Einheit des physikalischen Weltbildes. Von MAX PLANCK.
Leipzig: S. Hirzel, 1909. 8vo, pp. 38. M. 1.25.

The publication of these lectures by one of the most stimulating and successful of the professors at Berlin makes them available to a far wider circle than that which was able to hear them—at Columbia University in case of the eight first named, and at Leyden in case of the last.

They are written in the clear and logical style of their author, and in print they add much to the agreeable impression received by their hearers. The topics of the Columbia lectures are as follows: (1) Reversibility and Irreversibility; (2) Thermodynamic Conditions of Equilibrium in Dilute Solutions; (3) Atomic Theory of Matter; (4) Characteristic Equation of a Monatomic Gas; (5) Electrodynamical Theory of Heat Radiation; (6) Statistical Theory of Heat Radiation; (7) Principle of Least Action; (8) Principle of Relativity.

The Leyden lecture deals with the unity which the modern physicist regards as basic in his conception of the universe. The author traces some of the lines along which this physical conception may be expected to develop in future. He concludes with an affirmation of the objectivity of the laws of nature.

The lectures are handsomely printed, the first set in Latin type, the pamphlet in that attractive variation of the Latin occasionally used by the Germans for semi-popular works.

E. B. F.

The Natural History and Scientific Book Circular No. 145. London: William Wesley & Sons, 1910. Pp. 120. 1s.

This catalogue of manuscripts, books, and pamphlets on astronomy is of permanent value. The 3641 numbers are classified and arranged in sections of a few pages each, astrophysics being represented by more than 600 titles, while stellar astronomy has nearly as many. About 750 deal with the solar system and 900 with spherical, practical, and theoretical astronomy. The remainder consist of general works and periodical publications and an unusually complete and interesting selection of the older writers up to the middle of the eighteenth century. The latter section appeals to the epicure on the lookout for a find; the seeker of a particular book may prefer a quick lunch on a single long list of authors alphabetically arranged.

While the plan of the catalogue necessitates some duplication of titles—for such books as the *Selenographia* of Hevelius must obviously appear in at least two places—it makes the book worthy of a modest space on the shelf by the side of Houzeau's *Vade Mecum*. It is neatly bound and is sold for a shilling.

R. W. WILLSON

Tables du Bulletin de la Société belge d'astronomie (1895-1909).

By AUGUSTE COLLARD. Brussels: G. Van Oest & Cie., 1910. 8vo, pp. 123. Paper, Fr. 3.

This is a general index by subjects and by authors to Vols. I-XIV of the *Bulletin*—all that were published before the *Bulletin* was merged with *Ciel et Terre* in January of this year. It is the fourth of a series of twenty general indices of Belgian publications to be published by the *Association des archivistes et bibliothécaires belges*. As there are sixteen indices yet to appear, presumably following the same general plan, it may be of use to point out what seems to be a serious fault. The subject index does not give volume and page directly, but refers to the author index for them, and thus doubles the work of consulting it without any saving in space whatever. There is other evidence that the subject index has been less carefully treated than the author index. The appearance of the catch-words Manora, Paris, Rio Janeiro, Yale,

etc., leads one to expect to find other observatories listed under Belgique, Harvard, Lick, Yerkes, but in vain; they, with others, are to be found only under "Observatoire." Now, if under the latter catch-word were listed *all* titles properly coming under this head, no great harm might be done. This is unfortunately not the case; see, for instance, Greenwich, Grenade, Meudon, and Uccle.

S. B. B.

Geographical Essays. By WILLIAM MORRIS DAVIS. Boston: Ginn & Co., 1909. Pp. 777, with 130 diagrams. \$2.75.

At the close of Professor Davis' course of lectures at the University of Berlin last winter, a German professor was asked what sort of impression Professor Davis had made upon the Germans. He replied with great enthusiasm, "Prachtvoll!" The same term might well be applied to the impression produced by this collection of essays. The essays are especially adapted to the use of advanced students and teachers of physical geography, but their style is so clear, concise, and interesting that they furnish good reading for anyone, whether especially interested in geography or not.

The book is divided into two parts: Part I, "Educational Essays"; Part II, "Physiographic Essays." In the first part Professor Davis appears as a pioneer defining his subject in "An Inductive Study of the Content of Geography"; pleading for the introduction of physical geography into school, college, and university, in five essays; and dealing with the methods of teaching geography in four more.

In Part II are found some of the results of Professor Davis' researches. The three essays on "The Geographical Cycle" read like an interesting story. Such general subjects as plains, rivers and valleys, river-terraces, and glacial action are treated, and several essays are devoted to the geographical investigation of special regions ranging from "The Outline of Cape Cod" to "The Mountain Ranges of the Great Basin."

These essays are not new, but have been collected from twenty different sources and are now rendered more conveniently accessible in this one volume.

FREDERICK SLOCUM

NOTICE

The scope of the *ASTROPHYSICAL JOURNAL* includes all investigations of radiant energy, whether conducted in the observatory or in the laboratory. The subjects to which special attention is given are photographic and visual observations of the heavenly bodies (other than those pertaining to "astronomy of position"); spectroscopic, photometric, bolometric, and radiometric work of all kinds; descriptions of instruments and apparatus used in such investigations; and theoretical papers bearing on any of these subjects.

Articles written in any language will be accepted for publication, but unless a wish to the contrary is expressed by the author, they will be translated into English. Tables of wave-lengths will be printed with the short wave-lengths at the top, and maps of spectra with the red end on the right unless the author requests that the reverse procedure be followed.

Accuracy in the proof is gained by having manuscripts typewritten, provided the author carefully examines the sheets and eliminates any errors introduced by the stenographer. It is suggested that the author should retain a carbon or tissue copy of the manuscript, as it is generally necessary to keep the original manuscript at the editorial office until the article is printed.

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Authors are particularly requested to employ uniformly the metric units of length and mass; the English equivalents may be added if desired.

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